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Case Study for Delineating a Contributing Area to a Water-Supply Well in a Fractured Crystalline-Bedrock Aquifer, Stewartstown, Pennsylvania

by Gary J. Barton, Dennis W. Risser, Daniel G. Galeone, and Randall W. Conger

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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	43.81	liters per second
inch per year (in/yr)	25.4	millimeter per year
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Temperature	
degree Fahrenheit (°F)	°C=5/9 (°F-32)	degree Celsius

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in report:

- mg/L, milligrams per liter
- µg/L, micrograms per liter
- µS/cm, microsiemens per centimeter at 25 degrees Celsius
- pCi/L, picoCuries per liter

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ABSTRACT

The Trouts Lane well field in Stewartstown, Pa., was selected as a case study for delineating a contributing area in a fractured crystalline-bedrock aquifer. The study emphasized the importance of refining the understanding of boundary conditions and major heterogeneities that affect ground-water movement to the supply well by conducting (1) fracture-trace mapping, (2) borehole logging and flow measurements, (3) ground-water level monitoring, (4) aquifer testing, and (5) geochemical sampling. Methods and approach used in this study could be applicable for other wells in crystalline-bedrock terranes in southeastern Pennsylvania.

Methods of primary importance for refining the understanding of hydrology at the Trouts Lane well field were the aquifer tests, water-level measurements, and geophysical logging. Results from the constant-discharge aquifer test helped identify a major north-south trending hydraulic connection between supply well SW6 and a domestic-supply well. Aquifer-test results also indicated fractures that transmit most water to the supply well are hydraulically well-connected to the shallow regolith and highly weathered schist. Results from slug tests provided estimates of transmissivity and the nonuniform distribution of transmissivity throughout the well field, indicating the water-producing fractures are not evenly distributed and ground-water velocities must vary considerably throughout the well field. Water levels, which were easy to measure, provided additional evidence of hydraulic connections among wells. More importantly, they allowed the water-table configuration to be mapped. Borehole geophysics and flow measurements within the well were very useful because results indicated water entered supply well SW6 through bedrock fractures at very shallow depths—less than 60 ft below land surface; therefore, the area providing recharge to the well is probably in the immediate vicinity.

Preliminary delineations of the contributing area and the 90-day time-of-travel area were computed from a steady-state water budget and a time-of-travel equation. This easy approach provides insight into the size (but not the shape) of contributing areas. Three other approaches were used to refine the contributing-area shape: (1) uniform-flow equation, (2) water-table mapping, and (3) numerical modeling. The contributing areas computed from each approach differed depending on the simplification of the hydrogeologic framework that was made in each method of analysis. Although the approaches vary in complexity, regardless of the approach used, an estimate of the water-table configuration in the vicinity of the well field was key for making the best possible delineation of the contributing area.

A major limitation of this investigation was the inability to refine the delineation of the time-of-travel area. A time-of-travel area is based on the distance water travels in a given time. Because a few discrete fractures probably supply a significant amount of water to supply well SW6, the effective porosity (and hence, traveltime) of ground water is best estimated using tracers.

INTRODUCTION

The 1986 Amendments to the Safe Drinking Water Act required States to establish wellhead-protection (WHP) programs to protect ground water used for public supplies from possible contamination (U.S. Environmental Protection Agency, 1989). A critical element of every WHP program is the delineation of a wellhead-protection area, which is the surface area and subsurface volume of aquifer through which contaminants are reasonably likely to move on their paths to reach a water well (U.S. Environmental Protection Agency, 1987, p. 1-2). Many methods can be used to delineate the surface and subsurface parts of an aquifer contributing water to a well, but results can vary widely depending on the assumptions made with the application of each method and on the hydrogeologic setting in which they are applied. Recognizing this, the U.S. Geological Survey (USGS) in cooperation with the Pennsylvania Department of Environmental Protection (PaDEP) evaluated methods for delineating the contributing area for public-supply wells in differing hydrogeologic settings throughout Pennsylvania.

The USGS evaluation of methods to delineate contributing areas to wells in valley-fill aquifers in Pennsylvania was reported in Risser and Madden (1994), and a strategy for delineating contributing areas to wells in fractured bedrock aquifers was outlined in Risser and Barton (1995). The strategy for fractured bedrock aquifers was developed from three hydrogeologic field studies at public-supply wells selected to represent the wide range of hydrogeologic settings encountered by communities establishing WHP programs. Field studies were conducted in 1990 and 1991 at wells in (1) fractured crystalline bedrock at Stewartstown, (2) fractured sandstone and shale at Lansdale, and (3) karstic carbonate bedrock at Houserville (fig. 1).

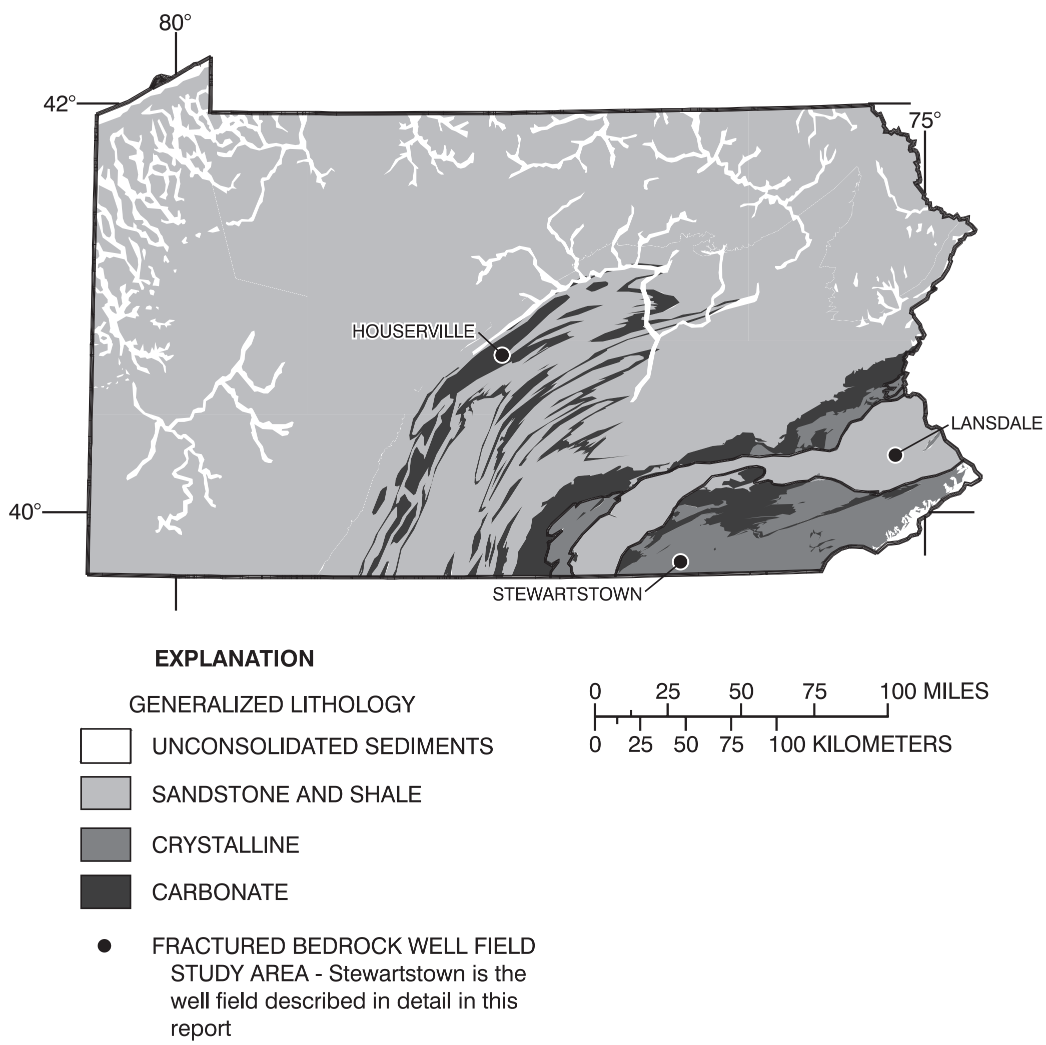


Figure 1. Generalized geology of Pennsylvania and location of fractured-bedrock study areas.

Purpose and Scope

This report describes the hydrogeologic field study of the fractured crystalline-bedrock aquifer at Stewartstown, Pa., conducted in 1991. The Trouts Lane well field at Stewartstown was selected for study because it represents hydrogeologic conditions characteristic of crystalline-bedrock aquifers in Pennsylvania. Crystalline-bedrock aquifers composed of metamorphic and igneous rocks such as schist, granite, phyllite, and gneiss are an important source of potable water in the Piedmont, Blue Ridge, and New England Physiographic Provinces of southeastern Pennsylvania. Withdrawals of ground water for public supply from the crystalline-bedrock aquifers in Pennsylvania averaged about 7.4 Mgal/d during 1990 (Mathey, 1990).

The hydrogeologic investigation at the Trouts Lane well field is presented as a case study to illustrate the strategy to delineate contributing areas as applied to wells in fractured crystalline-bedrock aquifers. The report also illustrates the differences in results from various approaches to delineate contributing areas. The study focused on the collection of hydrogeologic information and refinement of the hydrogeologic framework and conceptual model of the ground-water-flow system in the immediate vicinity of the well field. Field measurements of regional conditions outside of the well field, such as water-table configuration and base flow to streams, were outside the scope of this study.

Contributing Area and Related Terms

As used in this report, the aquifer volume through which water is drawn (or diverted) to a well is called the zone of diversion (fig. 2A). The projection of this aquifer volume to land surface defines the area of diversion to the well. The contributing area is the area of diversion and any adjacent areas that provide recharge to the aquifer within the zone of diversion. The contributing area may be equivalent in size to the area of diversion, but the contributing area can be much larger. For example, if it can be demonstrated that pumping from a well induces substantial flow from a stream as shown in figure 2A, the contributing area to the well includes a large area draining to the stream (fig. 2B). In such a case, it may be impractical to implement a WHP program throughout the watershed, but the source of water from the stream is an appreciable part of the total contribution. The part of the area of diversion from which water will reach a well within a specified time is a time-of-travel area (fig. 2B). It is always an area around the well that is less than or equal to the size of the area of diversion.

The area of diversion and contributing area as defined here relate to WHP Zones II and III in the Pennsylvania WHP program (Commonwealth of Pennsylvania, 1994). A hydrogeologically determined Zone II is equivalent to the area of diversion unless a radius of 0.5 mi is used instead. WHP Zone III equals those parts of the contributing area exclusive of the area of diversion. For example, Zone III equals the watershed of the stream (fig. 2B). The Pennsylvania WHP program Zone I is a circular area surrounding the well with a radius from 100 to 400 ft, determined from a method based on the volumetric flow equation (U.S. Environmental Protection Agency, 1987) as described in Pennsylvania Department of Environmental Protection (1995).

Strategy for Delineating the Contributing Area

Delineating a contributing area to a well completed in a fractured crystalline-bedrock aquifer is difficult because the hydrogeologic characteristics of fractured rocks are complex. Because of this complexity, a single method or technique to delineate a contributing area is not applicable for most wells completed in fractured crystalline-bedrock aquifers. Therefore, rather than presenting a method to delineate a contributing area, a strategy (fig. 3) for refining the understanding of boundary conditions and major heterogeneities that affect ground-water movement and sources of water to a supply well was proposed by Risser and Barton (1995). The strategy consists of (1) developing an initial conceptual model of the hydrogeologic setting near the well field on the basis of a literature review, (2) developing a preliminary contributing-area delineation, (3) refining the initial conceptual hydrogeologic model by conducting field studies, and (4) refining the preliminary contributing-area delineation so that it reflects the refined conceptual hydrogeologic model. By use of this strategy, the improved understanding of the ground-water-flow system will lead to a technically defensible delineation of the contributing area. This report describes a case study illustrating that strategy in a fractured crystalline-bedrock aquifer.

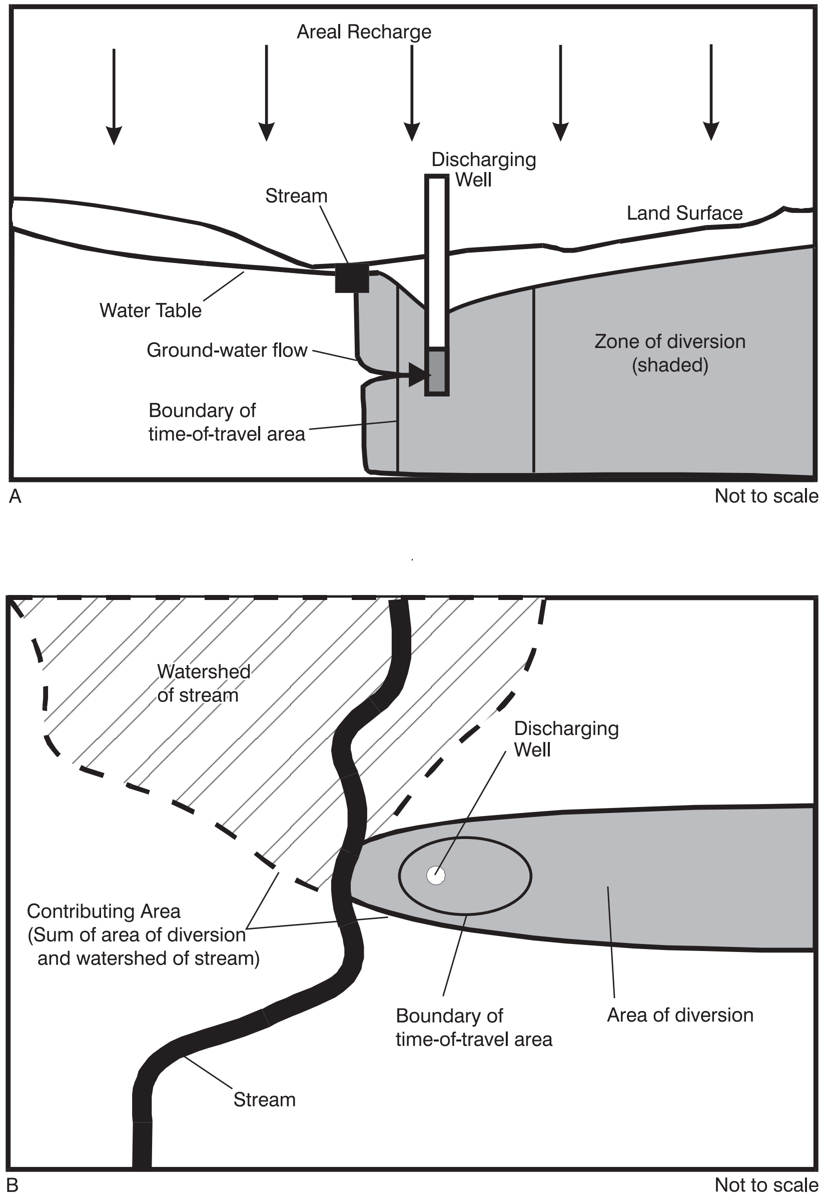


Figure 2. Area of diversion, contributing area, and time-of-travel area of a discharging well: (A) cross-sectioned view, (B) map view. (Modified from Reilly and Pollock, 1993, fig. 2.)

Description of the Well Field

The Trouts Lane well field is located in a 0.2-mi^2 watershed of an unnamed tributary to Ebaughs Creek near the divide between the Deer Creek and Muddy Creek Basins (fig. 4). The rolling topography and regolith-mantled schistose bedrock underlying the well field are typical of crystalline-bedrock terranes in the Piedmont Physiographic Province.

For the purpose of this report, the wells used for this study along Trouts Lane are referred to as the Trouts Lane well field. In 1991, the Trouts Lane well field consisted of a supply well (SW6) completed in bedrock of the Wissahickon Formation, four observation wells (OB1, OB2, OB3, and OB4) completed in the Wissahickon Formation, and four shallow piezometers (P2, P3, P4, and P5) completed in regolith (fig. 5 and table 1). Observation

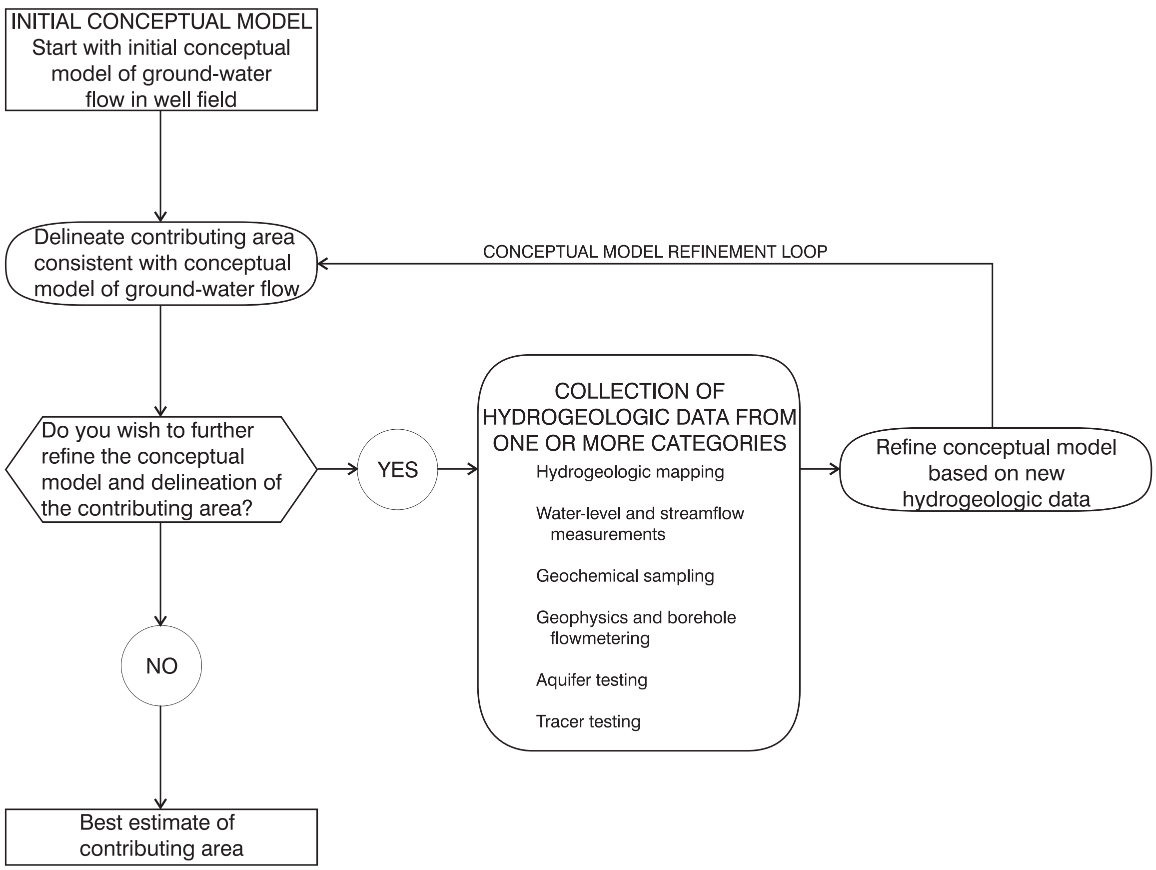


Figure 3. Overall strategy for delineating contributing areas in fractured crystalline-bedrock aquifers.

wells OB1, OB2, and OB3 were originally drilled as exploratory wells by the Borough of Stewartstown in their efforts to locate a water-supply well. Observation well OB4 was drilled by the USGS in an attempt to intersect the same fracture zone that yields water to supply well SW6. In addition, six nearby homeowners provided information or allowed water levels to be measured in their wells (D4, D6, D8, D10, D12, and D14) periodically during the study. These domestic-supply wells were the only wells withdrawing ground water from the well field area in 1991 because supply well SW6 was not connected to the public water-distribution system. At that time, water for the Borough of Stewartstown was supplied by withdrawals of about 75 gal / min from six wells completed in the Wissahickon Schist about 0.75 mi north of the Trouts Lane well field (fig. 4). The Borough of Stewartstown has since applied to PaDEP for a permit to operate supply well SW6 at a maximum rate of 50 gal / min.

ACKNOWLEDGMENTS

This project would not have been possible without assistance from several individuals: Robert Hunt, Borough of Stewartstown Manager, provided access to the Trouts Lane well field and information about the area; and Dennis Sarpen of James R. Holley and Associates allowed the USGS to collect data during their test pumping at supply well SW6. The assistance of nearby residents also is acknowledged for allowing water-level measurements to be made in their domestic-supply wells during the test pumping.

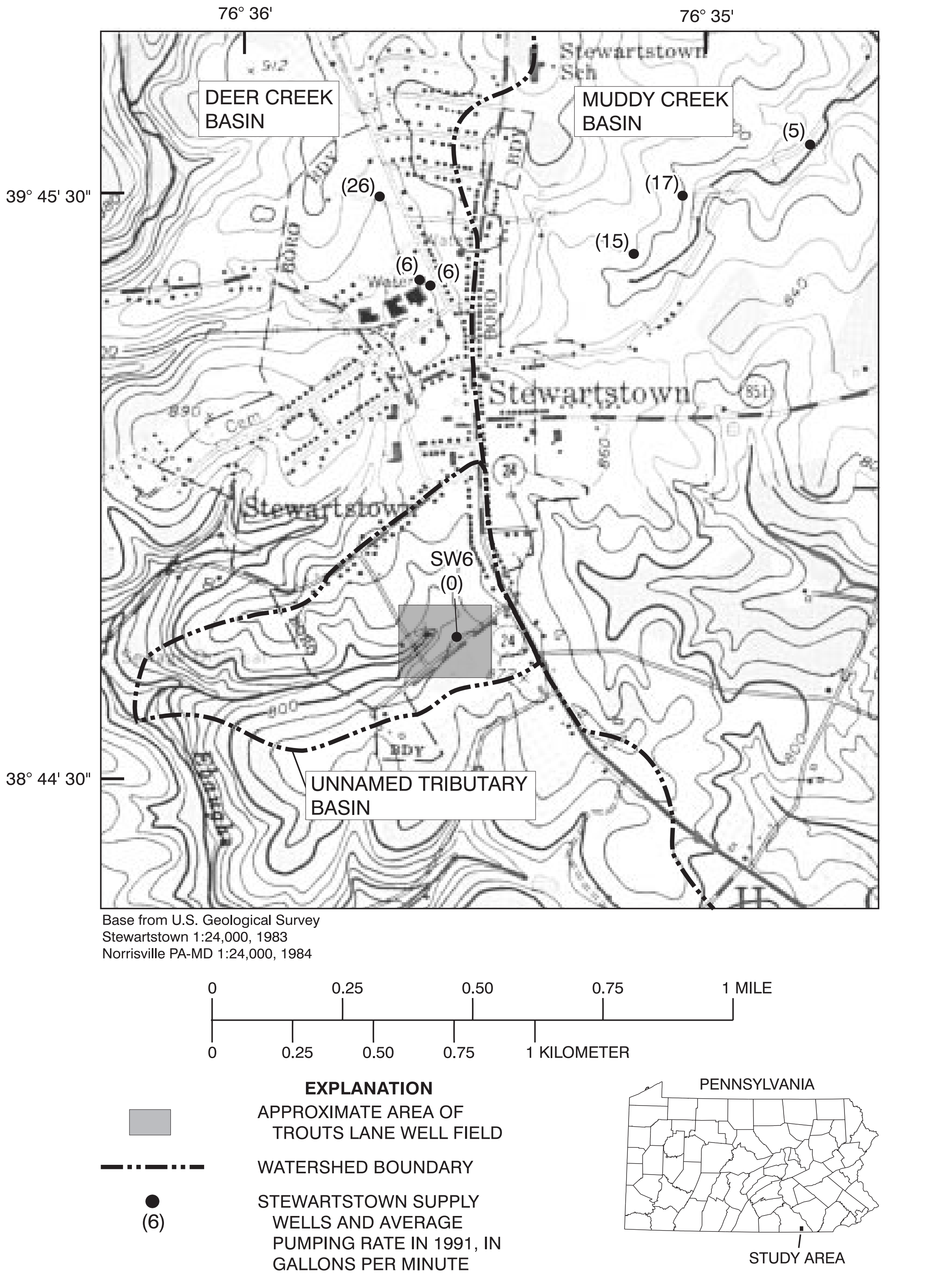
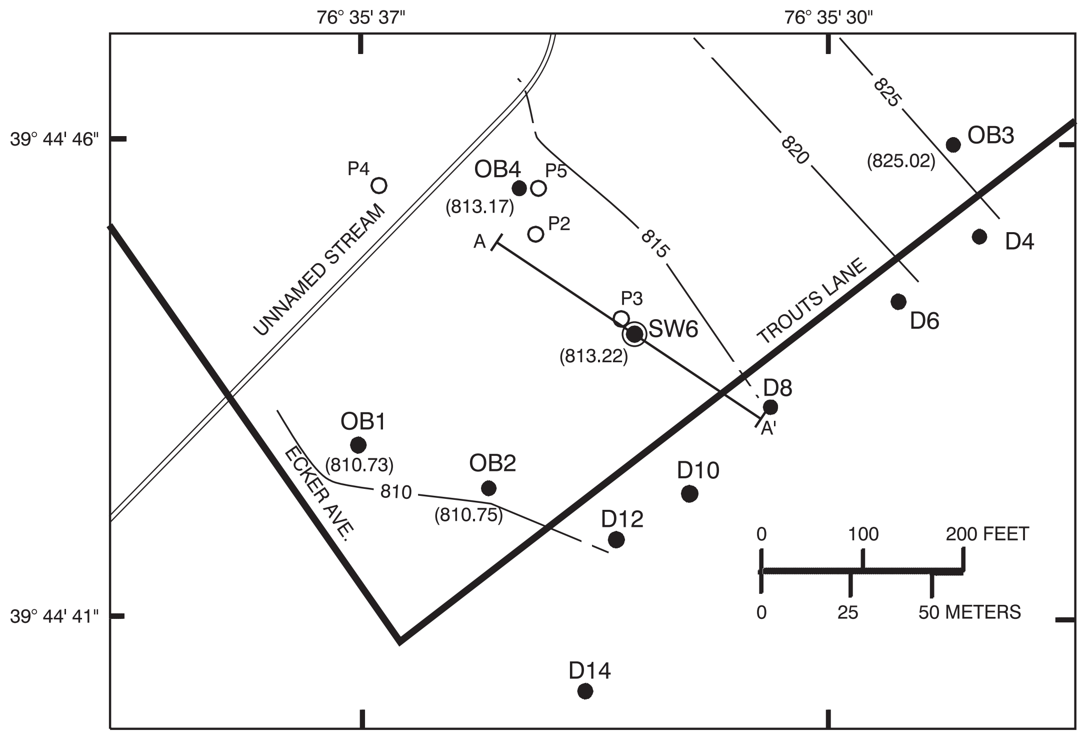


Figure 4. Location of Trouts Lane well field, Stewartstown, Pa.



EXPLANATION

– 810 – WATER-TABLE CONTOUR, shows altitude of the water table. Contour interval 5 feet. Datum is sea level. Contour dashed where approximately located.

A |——| A' TRACE OF CROSS SECTION SHOWN IN FIGURE 9.

LOCATION AND LOCAL IDENTIFIER OF:

● OB1 (810.73) Observation well completed in bedrock and altitude of ground-water level above sea level

● D4 Domestic well (household supply) complete in bedrock

○ P2 Piezometer completed in regolith

◉ SW6 (813.22) Public supply well completed in bedrock and altitude of ground-water level above sea level

Figure 5. Location of wells at the Trouts Lane well field, Stewartstown, Pa., and the altitude of water levels in bedrock wells on June 4, 1991.

Table 1. *Record of wells for the Trouts Lane well field, Stewartstown, Pa.*

[ft/d, feet per day; H, domestic; O, observation; P, public water supply; C, caliper; D, driller's; E, electric; F, fluid minute]

Local well identifier	U.S. Geological Survey well number	Latitude (°,′,″)	Longitude (°,′,″)	Principal aquifer	Date completed	Use	Altitude of land surface (feet above sea level)
SW6	YO-1173	39°44′44″	76°35′33″	Wissahickon Schist	3/29/1991	P	828.34
OB1	YO-1174	39°44′43″	76°35′37″	Wissahickon Schist	1/31/1991	O	815.40
OB2	YO-1187	39°44′42″	76°35′35″	Wissahickon Schist	5/--/1990	O	824.82
OB3	YO-1188	39°44′46″	76°35′29″	Wissahickon Schist	[1]4/11/1991	O	839.92
OB4	YO-1189	39°44′45″	76°35′34″	Wissahickon Schist	4/7/1991	O	818.27
D8	YO-1190	39°44′43″	76°35′31″	Wissahickon Schist	--	H	839.59
D10	YO-1191	39°44′42″	76°35′32″	Wissahickon Schist	--	H	840.92
D12	YO-1192	39°44′42″	76°35′33″	Wissahickon Schist	--	H	837.83
D14	YO-1193	39°44′40″	76°35′34″	Wissahickon Schist	--	H	842.39
P2	YO-1210	39°44′45″	76°35′34″	Regolith	4/9/1991	O	818.92
P3	YO-1211	39°44′44″	76°35′33″	Regolith	4/11/1991	O	827.77
P4	YO-1212	39°44′45″	76°35′36″	Regolith	4/11/1991	O	820.24
P5	YO-1213	39°44′45″	76°35′34″	Regolith	4/15/1991	O	819.29

[1] Date of rehabilitation of existing abandoned well.
[2] Cased with slotted PVC pipe.

DELINEATING THE CONTRIBUTING AREA

Initial Conceptual Hydrogeologic Model

An initial conceptual hydrogeologic model of ground-water flow to the Trouts Lane supply well SW6 was developed from published information describing general hydrogeologic conditions of regolith-mantled crystalline rocks. The conceptual model (fig. 6) and some information on aquifer properties are summarized below.

The regolith-mantled schist of the Wissahickon Formation of late Paleozoic age forms the geologic framework of the well field. Water-producing fractures in the Wissahickon Formation are sparse; thus, most ground water is present at shallow depths in pore spaces of the regolith and in fractures of the uppermost weathered part of the schist. According to Lloyd and Growitz (1977), the greatest density of water-producing zones in the bedrock is within 150 ft of land surface. Ground water in the regolith and shallow weathered schist generally is unconfined, but in the underlying sparsely fractured schist, ground water can be present under confined conditions. Because fractures in the schist that supply sustainable quantities of water to wells are connected hydraulically to unconfined ground water stored in the overlying regolith and continuous confining beds are lacking, Gerhart and Lazorchick (1988) describe this as a complex unconfined aquifer.

Water-producing fractures in the Wissahickon Formation near Stewartstown probably are aligned with the foliation of bedrock that trends northeast to southwest (Lloyd and Growitz, 1977). Because of this probable alignment, hydraulic conductivity is expected to be anisotropic with its maximum value aligned parallel with the foliation. Hydraulic conductivity of the regolith-mantled schist ranges from about 0.04 to 28 ft/d based on specific-capacity data from 61 wells throughout southeastern Pennsylvania. Gerhart and Lazorchick (1988) used an average of 1.34 ft/d for hydraulic conductivity

conductivity; J, gamma ray; T, temperature; V, fluid velocity; <, less than; --, data not available; gal/min, gallons per

Total depth below land surface (feet)	Casing		Driller-reported depth to water-bearing zone(s) (feet)	Horizontal hydraulic conductivity (ft/d)	Yield (gal/min)	Geophysical logs	Local well identifier
	Depth (feet below land surface)	Diameter (inches)					
392	40	8	59 / 115 / 160 / 241 / 284	8.11	50	C, D, E, F, J, T, V	SW6
200	38	6	96 / 123	.038	2	C, D, E, F, J, T, V	OB1
100	41	6	44	1.20	40	C, D, E, F, J, T, V	OB2
300	38	6	66	.962	--	C, E, F, J, T, V	OB3
300	40	6	--	.005	<1	--	OB4
--	--	6	--	--	--	--	D8
--	--	6	--	--	--	--	D10
--	--	6	--	--	--	--	D12
--	--	6	--	--	--	--	D14
9.2	[2]9.2	1	--	--	--	--	P2
18.8	[2]18.8	2	--	--	--	--	P3
8.2	[2]8.2	2	--	--	--	--	P4
19.1	[2]19.1	4	--	--	--	--	P5

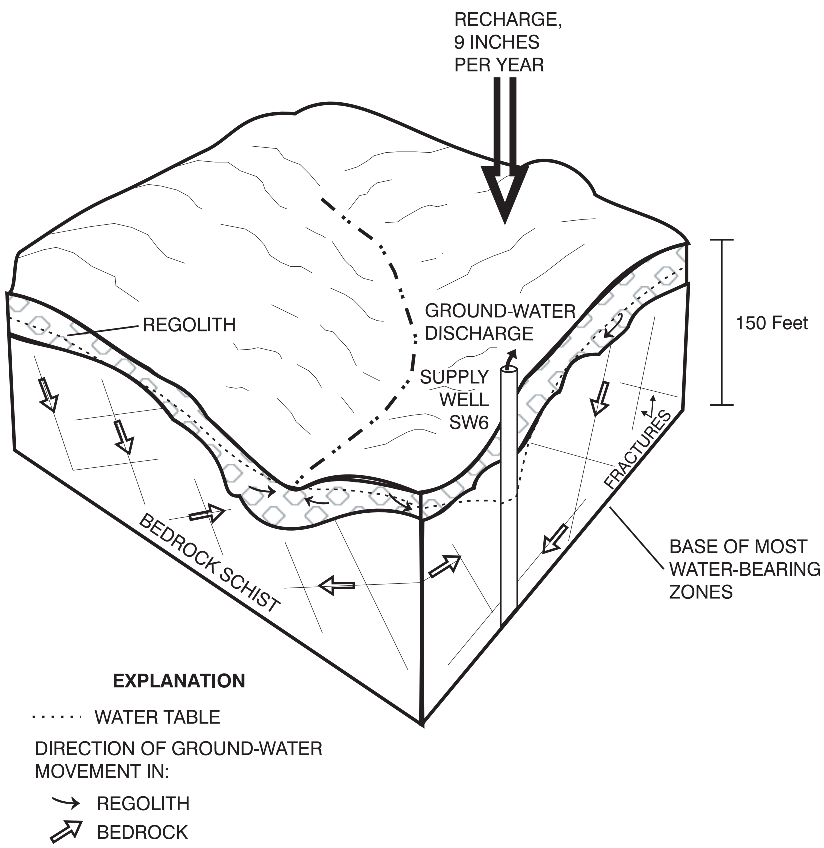


Figure 6. Preliminary conceptual model of ground-water flow to Trouts Lane supply well SW6, Stewartstown, Pa.

of the Wissahickon Formation near Stewartstown in their regional model of ground-water flow. Porosity and storage in the schist is low compared to the overlying regolith. Porosity generally is less than 2 percent for crystalline rocks (Heath, 1984). Porosity of the regolith generally ranges from 35 to 55 percent, and specific yield ranges from 8 to 24 percent. In the zone of water-level fluctuation, which includes regolith and weathered schist, Lloyd and Growitz (1977) estimated specific yield at 8 percent.

Most active ground-water circulation in this complex fractured-bedrock aquifer probably is in the upper tens of feet of regolith and weathered schist and probably is negligible at depths of 500 ft below land surface where fractures are sparse. Without measured water levels, the water table is assumed to be a subdued reflection of topography; thus, lateral ground-water basin boundaries are assumed to be coincident with topographic divides of the watershed. Ground-water recharge averages 8.2 to 10.1 in / yr in similar hydrogeologic settings in York County (Gerhart and Lazorchick, 1988, p. 29; Lloyd and Growitz, 1977, p. 28; Fishel and others, 1991, p. 23). Ground water in the well-field area discharges to an unnamed tributary of Ebaughs Creek, and small amounts of ground water are withdrawn by six wells for domestic use.

HYDROGEOLOGIC INVESTIGATIONS AT THE WELL FIELD

Hydrogeologic investigations were conducted at and in the vicinity of the Trouts Lane well field in 1991 to provide additional information about its hydrogeologic framework, boundary conditions, and aquifer properties. Additional information was incorporated into the conceptual hydrogeologic model to help refine delineations of the contributing area. Field investigations included geologic and fracture-trace mapping, borehole logging and flow measurements, ground-water level monitoring, aquifer testing, and geochemical sampling.

GEOLOGIC MAPPING

Geologic maps helped define the hydrogeologic framework at the well field. Geologic maps by Stose and Jonas (1939) indicate that the albite-chlorite schist of the Wissahickon Formation underlying the well field does not have any mappable faults, lithologic contacts, or major geologic structures that might act as barriers or preferred paths of ground-water flow. However, the geologic maps show a regional structural trend of N. 30° E. caused by Paleozoic mountain-building forces. Foliation of the schist should roughly parallel this orientation.

Although bedrock does not crop out at the well field, an examination of outcrops 3,600 ft to the west of the Trouts Lane well field showed that foliation in the Wissahickon Schist strikes about N. 30° E., nearly parallel to the regional deformational trend, and dips about 35° northwest. Numerous, nearly vertical joints were observed that cut the foliation at various angles.

Information obtained during drilling helped define the hydrogeologic framework in the vertical dimension. Driller records indicate that public-supply well SW6 and observation wells OB1 and OB2 were drilled through about 15 to 20 ft of regolith, 20 to 50 ft of weathered schist, and the remaining depth through hard competent schist. The saturated thickness of regolith and weathered schist averages about 30 ft. Construction records for supply well SW6 show the regolith and weathered schist have been cased off to 40 ft below land surface, and according to the driller’s log, ground water enters the well through fractures in the schist in the open-hole part of the well between 59 and 284 ft below land surface.

FRACTURE-TRACE MAPPING

Preferred avenues of ground-water flow to supply well SW6 were investigated on black and white, 1:24,000-scale aerial photographs by visually identifying linear traces that may indicate the presence of fracture zones. From the photos, linear traces could not be identified in the well field and vicinity.

Because straight-line stream segments can be affected by fractures, they were used as indications of fracture trends as suggested by Daniel (1989, p. B8). About 120 stream segments were mapped throughout an 8,000-ft radius around the well field. The segments were variously orientated (fig. 7); however, two dominant bearings at N. 30 E. and N. 50° W. are indicated. The N. 30° E. bearing closely parallels the foliation of the schist. The trend bearing N. 50° W. is nearly orthogonal to the foliation and is probably controlled by extension jointing. These preferential orientations along and orthogonal to foliation were documented by Cranford and others (1982) in a similar geologic setting in the Piedmont Physiographic Province of northern Virginia.

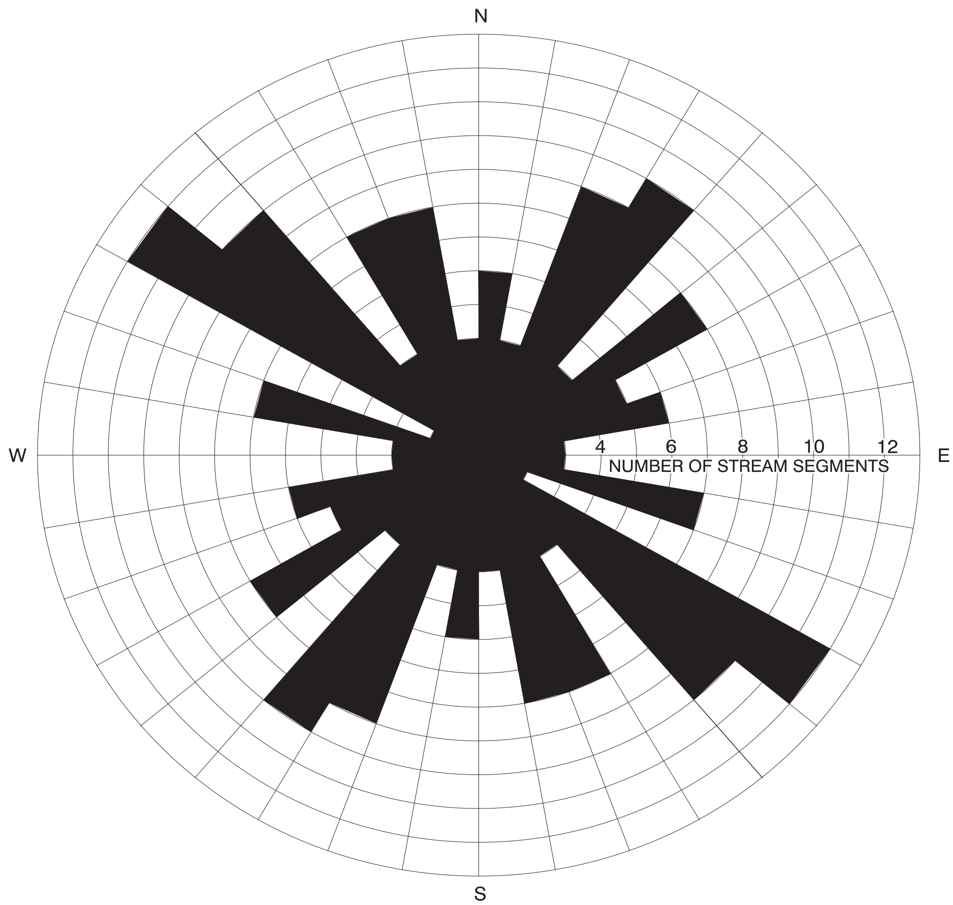


Figure 7. Trend and number of straight-line stream segments in and near the Trouts Lane well field, Stewartstown, Pa.

Borehole Geophysical Logging and Flow Measurements

Geophysical logging and measurements of vertical borehole flow were conducted in supply well SW6 and observation wells OB1, OB2, and OB3 to identify the water-producing fractures in each well and hydraulic connections among wells. Caliper, single-point resistance, and natural-gamma logs helped identify the location of fractures intercepted by the well, but not all fractures produced water. Inflections in fluid-temperature and fluid-resistivity logs showed which fractures produced water. Measurements of borehole flow by the brine-tracing method (Patten and Bennett, 1962) quantified the rate of vertical flow to a detection limit of about 0.5 gal / min. From the flow measurements and other logs, the location and relative yield of water-producing fractures were identified.

Caliper logging records the diameter of the borehole. Locations where the borehole diameter is larger than average commonly are locations of fractures that intersect the borehole. Caliper logging at the Trouts Lane well field indicated that locations of borehole enlargement (probable fracture locations) are sparse. The fracture density per foot of hole drilled was computed from locations of borehole enlargement identified on caliper logs from observation wells OB1, OB2, OB3, and supply well SW6. Fracture density decreased with depth from 0.075 fractures per foot from 40 to 90 ft below land surface to 0.013 fractures per foot from 90-219 ft below land surface. Fractures deeper than 219 ft below land surface were not confirmed by geophysical logging, although the driller reported water from 284 ft below land surface in supply well SW6. At SW6, the caliper log (fig. 8) shows major fractures at 40-42, 48-51, and 217-219 ft

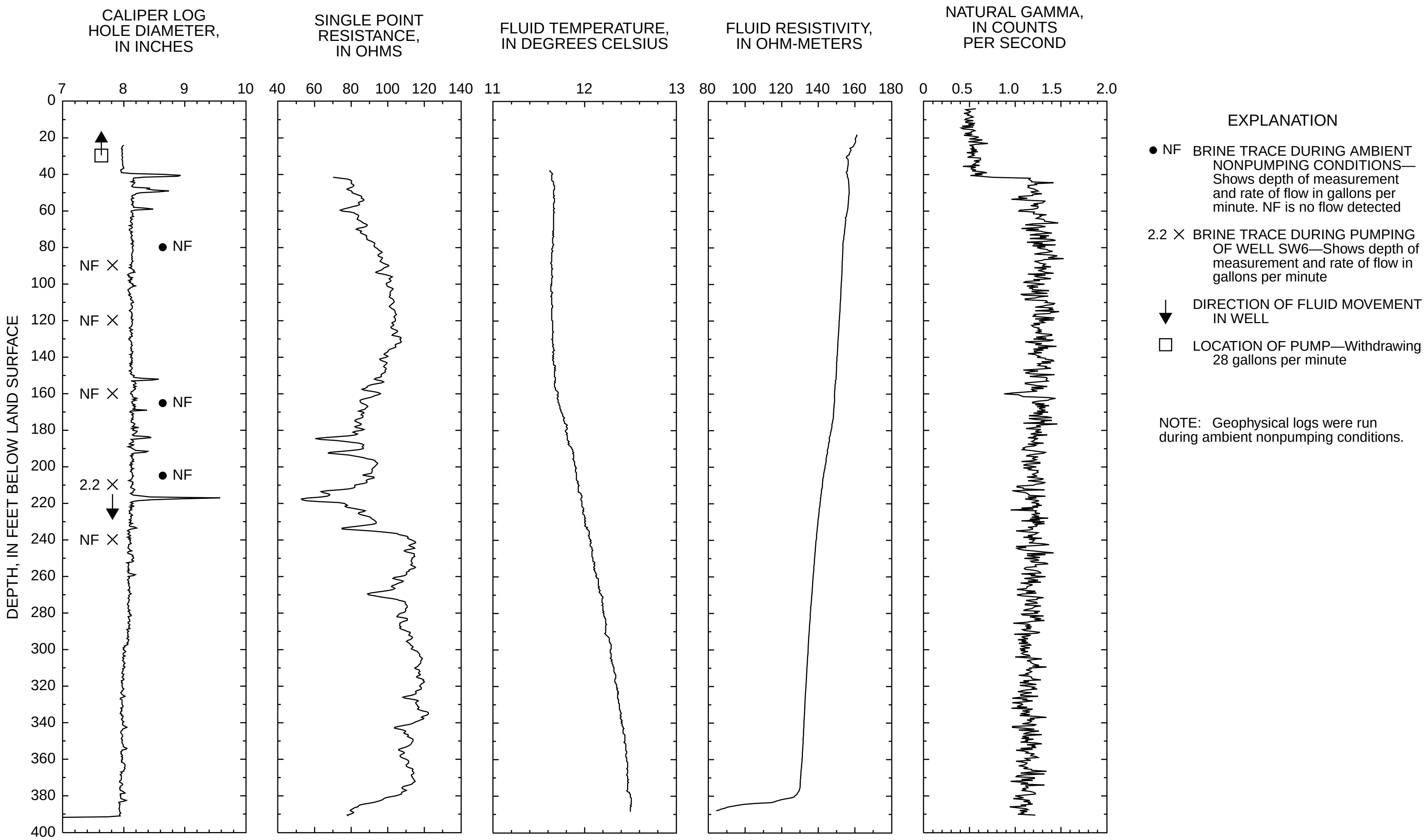


Figure 8. Borehole geophysical logs and brine-tracing results at Trouts Lane supply well SW6, Stewartstown, Pa.

below land surface and slight enlargements of the hole at 59-60, 152-154, 169-170, 184-185, and 192-193 ft below land surface that also could be fractures.

To identify which fractures yielded water to supply well SW6, measurements of fluid resistivity, fluid temperature, and vertical fluid flow within the borehole were made on July 24, 1991, under nonpumping conditions and while water was being pumped from the well. Under nonpumping conditions, flow within well SW6 was not indicated by any inflections on the fluid-resistivity and fluid-temperature logs. Flow measurements by brine tracing at 80, 165, and 205 ft below land surface also failed to detect any vertical movement of water within the well (fig. 8). Supply well SW6 was logged again while withdrawing water at a rate of 28 gal / min from a pump placed inside the casing approximately 30 ft below land surface. Flow measurements were made by brine tracing at 90, 120, 160, 210, and 240 ft below land surface (fig. 8). Vertical flow was not detected at 90, 120, 160, or 240 ft depths, indicating that most water is yielded to the well by fractures in the schist above 90 ft (most are between 40-60 ft) below land surface. However, this conclusion is complicated by a measurement of downward flow at 210 ft below land surface. Water apparently enters the well from a fracture about 180 ft below land surface, flows down the borehole at 2 gal / min, and exits the well into a fracture at about 217 ft below land surface. This downward flow in the well between 180 and 217 ft below land surface is difficult to explain. Possibly, the fracture at 217 ft below land surface is hydraulically connected to a domestic-supply well or Stewartstown public-supply well that is being pumped intermittently. This could explain why downward flow was not detected during flow measurements made during nonpumping conditions.

Geophysical logging also was conducted during a constant-discharge aquifer test at supply well SW6 during April 17-19, 1991, to identify hydraulic connections between supply well SW6 and observation wells OB1, OB2, and OB3. During the aquifer test, the hydraulic head was lowered in the water-producing fractures that were hydraulically connected to supply well SW6. These hydraulically connected fractures were identified by deflections in the fluid-resistivity and fluid-temperature logs and confirmed by flow measurements in the wells. In OB1, hydraulically connected water-producing fractures were not indicated by fluid logs or flow measurement. In OB2, a hydraulically connected fracture was indicated at 65 ft below land surface by an inflection on the fluid-resistivity log, although vertical fluid movement in the well could not be detected by brine-tracing measurements. Probably, ground water entered the well from a fracture at 45 ft below land surface and exited at 65 ft below land surface at a rate lower than could be detected by the flow-measurement technique. In well OB3, measurements of fluid resistivity and vertical flow showed that water entered the well from fractures between 64 and 93 ft below land surface, flowed down the well at 1 gal / min, and exited into a fracture at 169 ft below land surface. Thus, the fracture at 169 ft below land surface is hydraulically connected to the fractures yielding water to supply well SW6.

Apparently, some fractures in observation wells are hydraulically connected to fractures yielding water to supply well SW6, although the pathways of flow are not clear. Major water-yielding fractures that were confirmed by geophysical logging and flowmetering are shown in figure 9. Those fractures that were shown to be hydraulically connected to the fractures in well SW6 are shown in blue. Additional water-producing zones were reported by the driller (table 1) but could not be confirmed by geophysical logging. Note that the dip of foliation in the schist does not seem to affect the location of the hydraulically connected water-producing fractures.

Ground-Water Level Monitoring

To map the water-table configuration, investigate hydraulic interconnections between wells, and characterize the network of water-producing fractures, ground-water levels were measured continuously from April through October 1991 in all wells and piezometers at the well field.

Water-Table Mapping

A water-table map of the well field was contoured from water levels measured on June 14, 1991, in wells completed in the bedrock aquifer (fig. 5). The water table measured at the well field slopes to the south and southwest. The average hydraulic gradient upgradient of supply well SW6 is about 0.04 but varies throughout the well field from about 0.01 to 0.05. Also, a map of the water table in the surrounding area was estimated from water levels at the Trouts Lane well field, from two

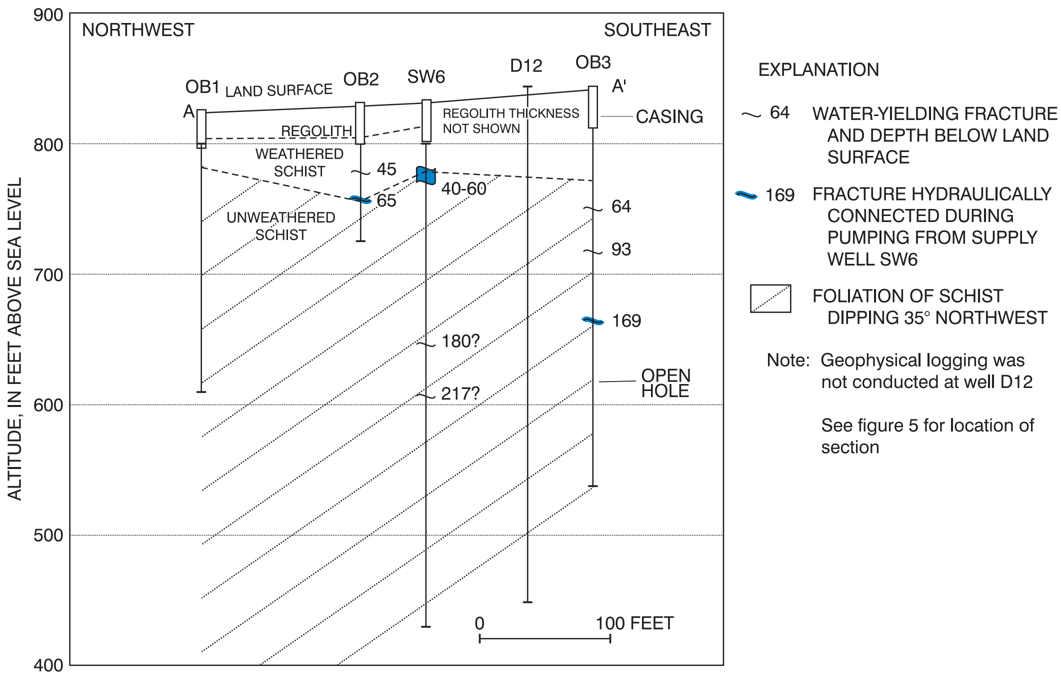


Figure 9. Cross section A-A′ showing locations of water-yielding fractures identified by geophysical logging and measurements of vertical flow with wells.

nearby wells, and from the altitude of perennial streams (fig. 10). The assumption that the water-table configuration can be estimated from topography and stream altitude is supported by water-table mapping in crystalline-bedrock terranes in Chester County, Pa. These maps, prepared on the basis of hundreds of water-level measurements in wells, show the water table to be a subdued representation of surface topography (Wettstein and Wood, 1996).

Response to Recharge and Nearby Pumping

The similarity of water-level fluctuations in nested well pairs, where a piezometer completed in regolith (P5) was drilled beside a well completed in bedrock (OB4), indicates the bedrock and overlying regolith are well-connected hydraulically and together form an aquifer under water-table conditions. When supply well SW6 was pumped at 28 gal/min for 3 hours on July 24, 1991, the water levels in P5 and OB5 each declined about 0.7 ft. The water-level response to pumping from supply well SW6 and to recharge in late September is nearly identical for both wells of the nested pair (fig. 11).

The water-level fluctuations caused by intermittent pumping from nearby domestic wells were used to evaluate hydraulic connections and infer the location of water-producing fractures. Cyclic pumping of one of the domestic wells caused nearly instantaneous water-level declines only in supply well SW6 (fig. 12A), indicating that a water-producing fracture or set of fractures hydraulically connect SW6 and one of the domestic wells. By pumping from supply well SW6 and monitoring water-level fluctuations in the domestic wells, it was discovered that pumping from domestic well D12 was responsible for the fluctuations shown in figure 12A.

Ground-water withdrawals from domestic-supply wells D4 and D6 on June 18-22, 1991, caused measurable water-level declines only in well OB3 (fig. 12B). Water levels in OB3 declined 0.25 ft on June 22 as a result of prolonged pumping from wells D4 and D6 to fill residential swimming pools. These declines indicate that wells D4 and D6 are hydraulically connected by an unknown configuration of water-producing fractures to OB3.

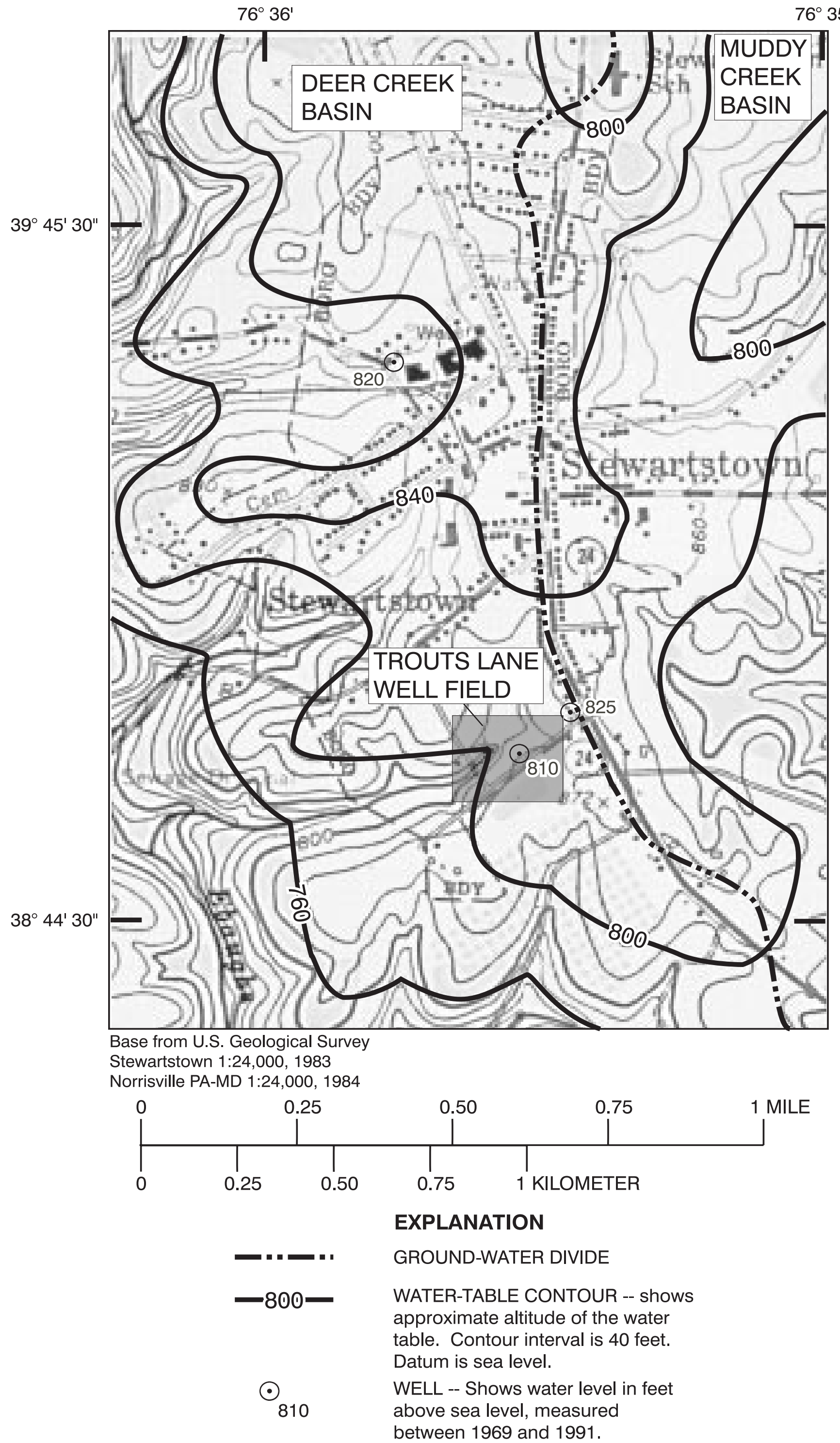


Figure 10. Estimated water-table altitude for the vicinity surrounding the Trouts Lane well field, Stewartstown, Pa.

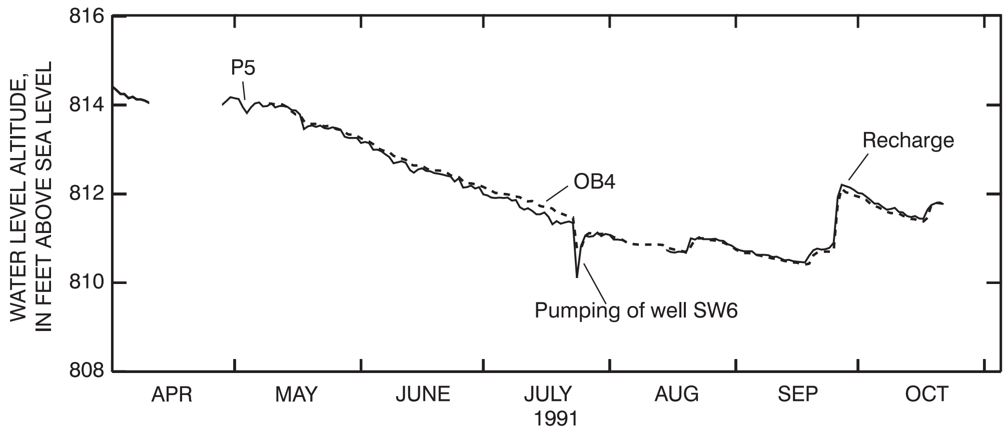


Figure 11. Altitude of water levels in nested regolith piezometer (P5) and bedrock well (OB4) at the Trouts Lane well field, Stewartstown, Pa., April-October 1991.

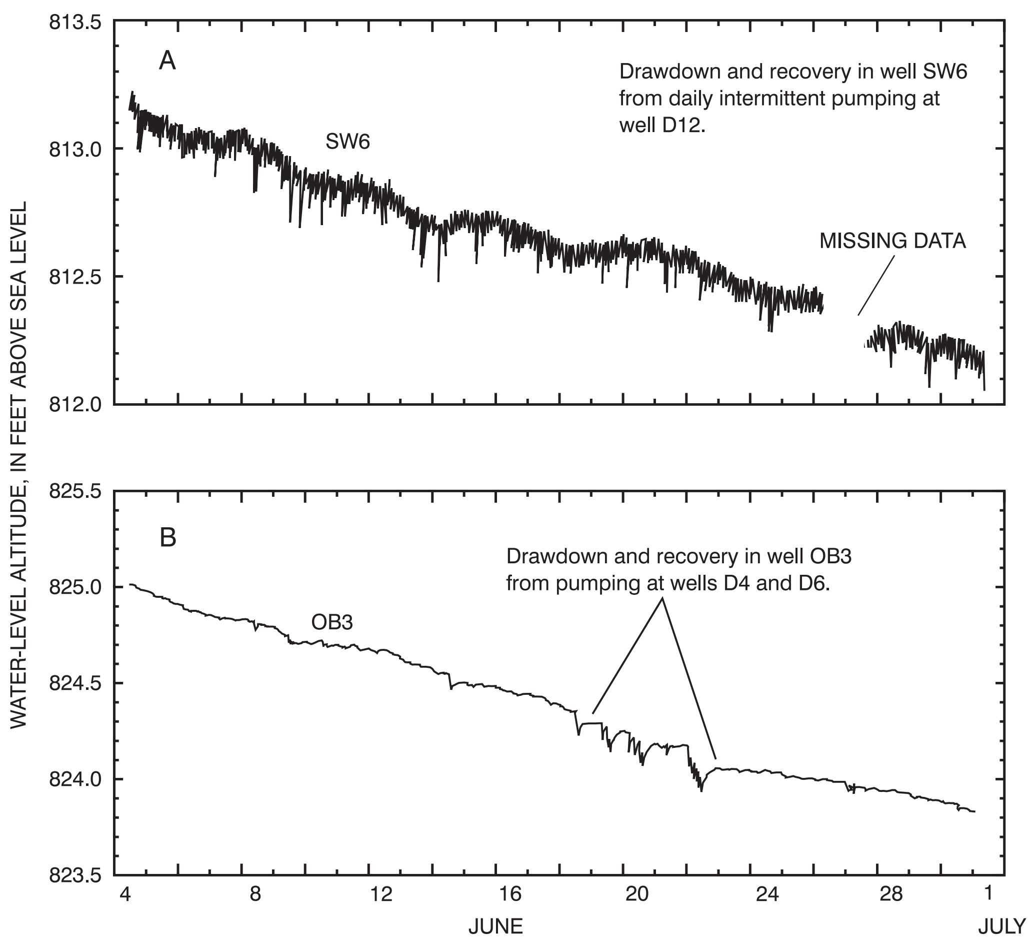


Figure 12. Water-level response in bedrock wells (A) SW6 and (B) OB3 because of intermittent pumping of nearby domestic wells.

Aquifer Testing

Slug Tests

Slug tests were conducted in the bedrock wells to estimate the transmissivity of the Wissahickon Formation at the Trouts Lane well field. The rise and fall of the water level in the wells caused by the sudden introduction of a displacement barrel was analyzed based on the method of Bouwer and Rice (1976). Water-level change in response to slug testing at each well is shown in figure 13.

The method of Bouwer and Rice (1976) was used to provide an estimate of the average hydraulic conductivity of the open interval of the well. Because wells completed in the sparsely fractured schist obtain water from only a small fraction of the open hole, the average hydraulic conductivity may not be very useful to describe the properties of this aquifer. Therefore, aquifer transmissivity (table 2) was computed by multiplying the hydraulic conductivity from each slug test by the saturated length of open hole at that well.

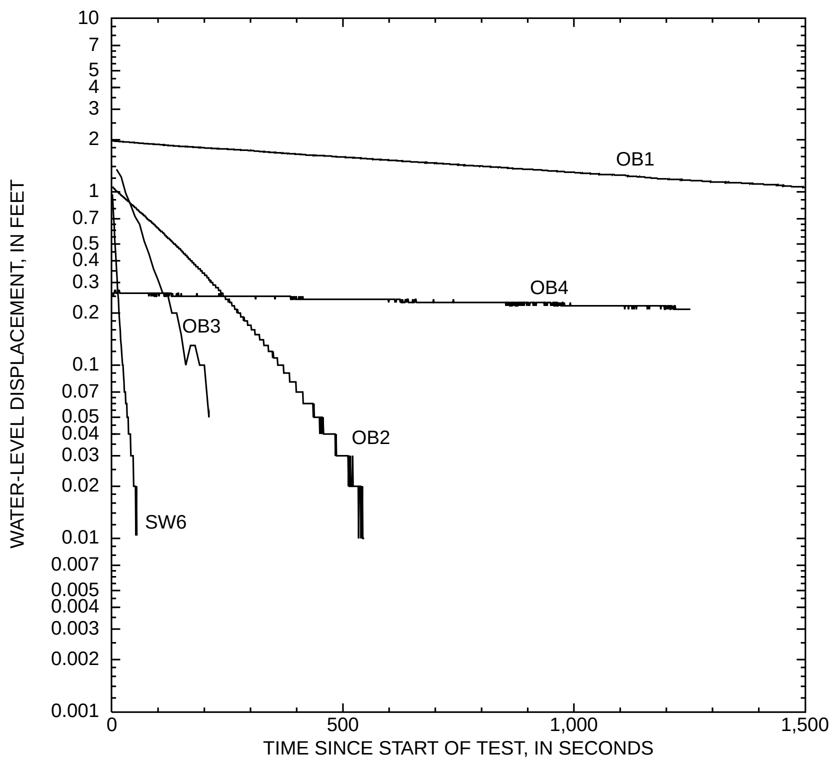


Figure 13. Water-level change in response to slug tests in wells at the Trouts Lane well field, Stewartstown, Pa.

Table 2. *Hydraulic conductivity and transmissivity determined from slug tests conducted at the Trouts Lane well field, Stewartstown, Pa.*

Local well identifier	Well depth (feet below land surface)	Saturated open-interval length (feet)	Hydraulic conductivity (feet per day)	Transmissivity (square feet per day)
SW6	392	352	8.1	2,850
OB1	200	162	.037	6.0
OB2	100	59	1.2	71
OB3	300	262	.96	250
OB4	300	260	.004	2.4

The slug-test results indicate that the hydraulic conductivity and transmissivity of the schist in the well field range at least three orders of magnitude. Hydraulic conductivity ranges from 0.009 ft / d at OB4 to 8.1 ft / d at SW6, with a geometric mean of about 1.6 ft / d. Transmissivity ranges from 2.4 ft^2 / d at OB4 to 2,850 ft^2 / d at SW6, with a geometric mean of about 60 ft^2 / d. The nonuniform distribution of hydraulic conductivity and transmissivity throughout the well field suggests that the geometry, distribution, and interconnection of fractures probably varies considerably; thus, ground-water velocities also probably vary greatly throughout the well field.

STEP-DRAWDOWN TEST

A step-drawdown test was conducted on supply well SW6 by pumping for successive 30-min intervals at rates of 48, 67, 83, and 108 gal / min (Dennis Sarpen, James Holley and Associates Inc., written commun., 1991). Drawdown per unit discharge of water increased nearly linearly for ground-water withdrawals less than 83 gal / min and drawdown of less than 25 ft (fig. 14). However, at a withdrawal rate of 108 gal / min, drawdown increased sharply to 89 ft. Step-drawdown plots with this concave-up shape represent the effect of increased turbulent flow and dewatering of water-yielding fractures (Mackie, 1982). Thus, the increase in slope for this test at supply well SW6 indicates that the bedrock fractures between 25 and 89 ft below land surface probably are major water-producing fractures. This supports the caliper logging and borehole-flow measurements that indicate most water enters well SW6 from fractures between 40 and 60 ft below land surface.

CONSTANT-DISCHARGE TEST

A 48-hour aquifer test was conducted at the well field on April 17-19, 1991. Supply well SW6 was pumped at 70 gal / min during the first 24 hours of the test; during the final 24 hours, the discharge was reduced to 50 gal / min to meet PaDEP requirements for permitting the supply well. Ground water withdrawn from SW6 was discharged to the unnamed tributary about 300 ft to

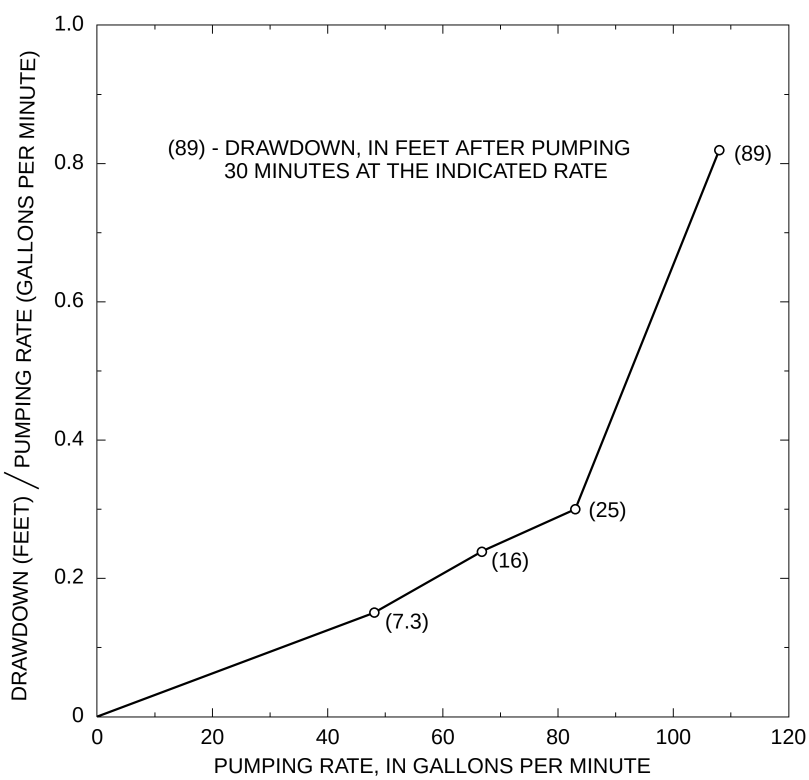
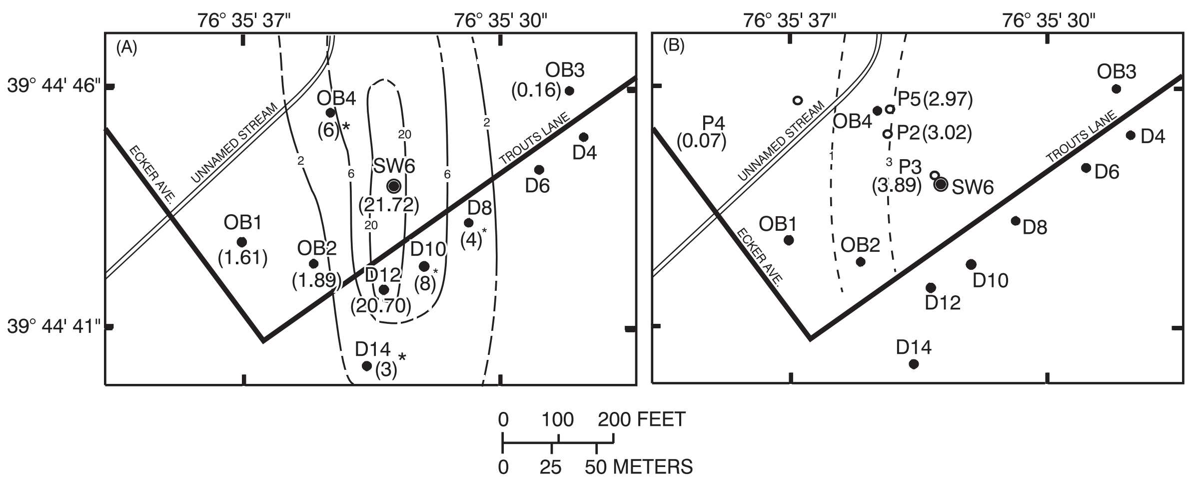


Figure 14. Step-drawdown pumping test at Trouts Lane supply well SW6, Stewartstown, Pa.

the west of the well. Water levels were monitored in four piezometers completed in regolith and eight wells completed in bedrock, including the supply well and four nearby domestic wells. Water levels in four bedrock wells were monitored prior to the test; no appreciable pre-test water-level trends were observed. Drawdown measured in the domestic-supply wells (D8 through D14) is approximate because periodic pumping by home-owners during the aquifer test temporarily increased drawdown in these wells, which made separating the effects of pumping caused by supply well SW6 difficult. Thus, the estimated drawdown from these wells is shown to the nearest foot (fig. 15A).

After 48 hours of pumping, drawdown in the wells completed in bedrock ranged from 0.16 ft in OB3 to 21.7 ft in supply well SW6. Drawdown did not stabilize during the first 24 hours of the test during which SW6 was pumped at 70 gal/min. After the pumping rate was decreased to 50 gal/min, drawdown stabilized in supply well SW6 and domestic well D12, but levels continued to decline in all other observation wells. Drawdown of 0.7 ft



EXPLANATION

— 4 — DRAWDOWN -- Shows line of equal drawdown, in feet, caused by pumping SW6, on April 19, 1991. Dashed where approximate. Contour interval variable.

LOCATION AND LOCAL IDENTIFIER OF:

● OB1 Bedrock observation well

● D6 Domestic bedrock well (household supply)

○ P5 Piezometer completed in regolith

◉ SW6 Bedrock supply well

(3)* Drawdown at the well, in feet, caused by pumping well SW6. Asterisk indicates estimated value.

Figure 15. Drawdown resulting from the pumping of Trouts Lane supply well SW6 for (A) bedrock wells after 48 hours of pumping, and (B) regolith piezometers after 8 hours of pumping, Stewartstown, Pa.

was measured in piezometer P4, located on the opposite side of the unnamed tributary from the pumped well, which indicates that the small stream is not a fully penetrating hydrologic boundary.

Drawdown caused by pumping from supply well SW6 is shown for wells completed in bedrock after 48 hours of pumping and for piezometers completed in regolith after 8 hours of pumping (fig. 15). Drawdown in the regolith was measured after only 8 hours (fig. 15B) because water levels declined below the bottom of piezometers P2 and P3 after about 8 hours of pumping. The drawdown in bedrock wells (fig. 15A) forms an elliptical cone-of-depression. The greatest drawdown is in a north-south trend between SW6 and D12. Drawdown in well D12 is much greater than in any other observation well or piezometer. Lloyd and Growitz (1977) observed a similar hydrologic response to pumping in the Wissahickon Formation and concluded that the magnitude of drawdown was dependent on the location of observation wells around the pumping well with respect to the orientation of schistosity. Because of the nearly north trend, the apparent anisotropy is more likely created by interconnected joints or a north-trending fracture than by the foliation that trends N. 30° E.

The drawdown curves for observation wells and piezometers were analyzed to quantify aquifer properties. The curves could not be fit to a consistent model for isotropic or anisotropic aquifers (Theis, 1935; Papadopulos, 1965). Curve matching showed that time-drawdown plots for wells most distant from supply well SW6 fit the Theis curve most closely. Drawdown from wells near supply well SW6 could not be fit to the curves. This observation is consistent with the expected results if pumping were from a fracture of limited extent. Flow might be radial far from the fracture and nearly linear near the supply well where the influence of the fracture on ground-water flow is dominant.

To evaluate whether a single fracture controls ground-water movement to supply well SW6, drawdown and the square root of time were plotted (fig. 16). The parallel declines in drawdown shown for wells D12 and SW6, and OB1 and OB2, are indicative of linear flow to a well as described by Jenkins and Prentice (1983). Linear flow can occur if the pumping well is connected to a fracture such that the linear fracture acts hydraulically as an extension of the well. Water enters this extended well perpendicular to the fracture trend in a linear rather than a radial pattern. If a single north-trending fracture controlled all ground-water flow, each time-drawdown curve in figure 16 would be linear and parallel. Not all slopes of water-level decline are parallel; thus, a system more complex than a single fracture is indicated in this case.

Ground water in the regolith must be hydraulically connected to the bedrock fractures that yield water to supply well SW6. This is indicated by water levels after 8 hours of pumping that declined below the bottom of piezometers P2 and P3, which are screened to the base of the regolith. The volume of regolith dewatered was roughly estimated to be about 300,000 ft^3 by assuming that the drawdown shown in figure 15B was symmetrical about supply well SW6. The volume of water withdrawn after 8 hours of pumping at 70 gal/min is about 4,500 ft^3. If these volumes are accurate, the specific yield of the regolith would need to be only about 1.5 percent (4,500/300,000) to enable the volume of dewatered regolith to hydraulically balance all the water withdrawn during the first 8 hours of the aquifer test. Although the specific yield and volume of dewatered regolith are not accurately known, this computation indicates that storage in the regolith can be appreciably lowered by pumping from supply well SW6. Because the regolith is cased off in supply well SW6, the regolith must be hydraulically connected to fractures in the schist.

When supply well SW6 was pumped at a rate of 50 gal/min during the last 24 hours of the aquifer test, a stable drawdown of about 22 ft and water level of about 38 ft below land surface was sustained in SW6. This level is not far above the principle water-yielding fractures between 40 and 60 ft below land surface. Continuous pumping at 50 gal/min during late summer months when water levels are naturally lower may dewater these shallow water-yielding fractures, making this withdrawal rate difficult to sustain.

GEOCHEMICAL SAMPLING

The concentrations of common ions, nutrients, and trace metals were nearly constant prior to and at the end of the 48-hour aquifer test (table 3). These constant concentrations indicate that the source of water to SW6 during the test probably remained relatively constant. Nitrate concentrations ranged from 5.0 to 5.7 mg/L and are consis-

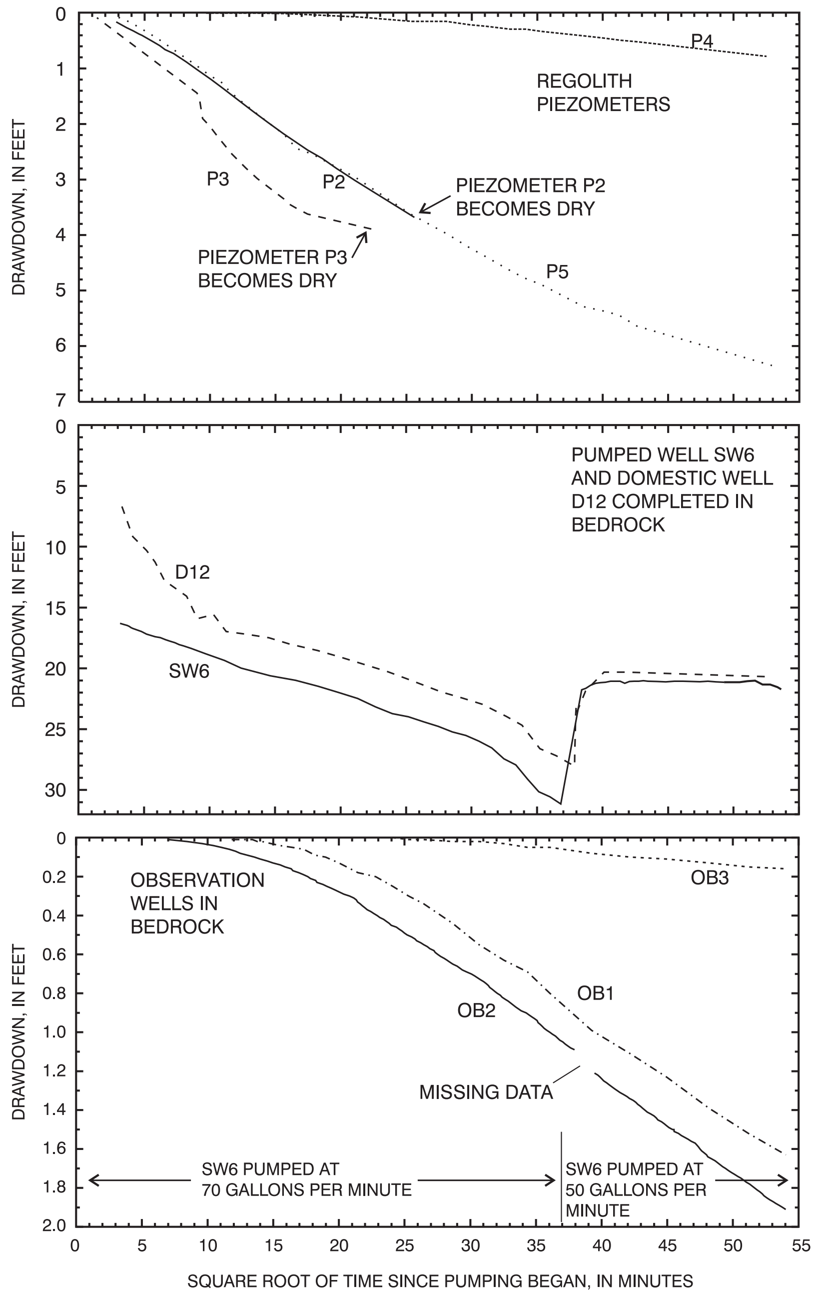


Figure 16. Drawdown during the 48-hour aquifer test at Trouts Lane supply well SW6, Stewartstown, Pa.

tent with a source of recharge from the agricultural land surrounding the well. The average nitrate concentration in ground water beneath agricultural lands in crystalline-rock settings in the lower Susquehanna River Basin was 7.5 mg/L on the basis of 22 samples collected in 1994 for the USGS National Water-Quality Assessment Program (Durlin and Schaftstall, 1996). Organic contaminants such as trichloroethylene that might indicate ground-water flow from a particular source area were not found. Tritium concentrations of 45 pCi/L sampled prior to the aquifer test and 50 pCi/L at the end of the test indicate that water withdrawn by the well probably recharged the aquifer less than 35 years ago (Davis and Murphy, 1987, p.40).

***Table 3.** Chemical analyses of ground-water samples collected near the beginning and end of pumping from supply well SW6 during the 48-hour aquifer test, Stewartstown, Pa.*

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picoCuries per liter; <, less than]

Parameter or chemical constituent	Beginning of test April 17, 1991 at 1140 hours	End of test April 19, 1991 at 0900 hours
Specific conductance (µS/cm)	137	136
pH (units)	5.8	5.6
Hardness, total (mg/L as $CaCO_3$)	37	34
Calcium, dissolved (mg/L as Ca)	8.0	7.0
Magnesium, dissolved (mg/L as Mg)	4.0	4.0
Sodium, dissolved (mg/L as Na)	8.6	9.1
Sodium adsorption ratio	.6	.7
Sulfate, dissolved (mg/L as SO_4)	3.1	.50
Chloride, dissolved (mg/L as Cl)	17	18
Fluoride, dissolved (mg/L as F)	<.10	<.10
Bromide, dissolved (mg/L as Br)	.041	.041
Silica, dissolved (mg/L as SIO_2)	9.3	8.6
Residue, total (mg/L)	<1	1
Nitrogen, nitrite, dissolved (mg/L as N)	<.010	<.010
Nitrogen, nitrite, total (mg/L as N)	<.010	<.010
$NO_2 + NO_3$, dissolved (mg/L as N)	5.2	5.30
$NO_2 + NO_3$, total (mg/L as N)	5.4	5.30
Nitrogen, ammonia, dissolved (mg/L as N)	<.010	<.010
Nitrogen, ammonia, total (mg/L as N)	<.010	<.010
Nitrogen, ammonia and organic, dissolved (mg/L as N)	<.20	<.20
Nitrogen, ammonia and organic, total (mg/L as N)	<.20	<.20
Phosphorus, ortho, dissolved (mg/L as P)	<.010	<.010
Phosphorus, ortho, total (mg/L as P)	.010	.010
Phosphorus, dissolved (mg/L as P)	<.010	<.010
Phosphorus, total (mg/L as P)	.030	<.010
Barium, dissolved (µg/L as Ba)	22	26
Beryllium, dissolved (µg/L as Be)	<.5	<.5
Cadmium, dissolved (µg/L as Cd)	<1.0	<1.0
Chromium, dissolved (µg/L as Cr)	<5	<5
Cobalt, dissolved (µg/L as Co)	<3	<3
Copper, dissolved (µg/L as Cu)	<10	<10
Iron, dissolved (µg/L as Fe)	27	21
Lead, dissolved (µg/L as {Pb)	10	<10
Lithium, dissolved (µg/L as Li)	<4	<4
Manganese, dissolved (µg/L as Mn)	18	13
Molybdenum, dissolved (µg/L as Mo)	<10	<10
Nickel, dissolved (µg/L as Ni)	<10	<10
Silver, dissolved (µg/L as Ag)	<1.0	<1.0
Strontium, dissolved (µg/L as Sr)	65	57
Vanadium, dissolved (µg/L as V)	<6	<6
Zinc, dissolved (µg/L as Zn)	620	570
Carbon, organic, total (mg/L as C)	.3	.4
Dichlorobromomethane (µg/L)	<3.0	<3.0

Table 3. *Chemical analyses of ground-water samples collected near the beginning and end of pumping from supply well SW6 during the 48-hour aquifer test, Stewartstown, Pa.—Continued*

Parameter or chemical constituent	Beginning of test April 17, 1991 at 1140 hours	End of test April 19, 1991 at 0900 hours
Carbontetrachloride (µg/L)	<3.0	<3.0
1,2-Dichloroethane (µg/L)	<3.0	<3.0
Bromoform, total (µg/L)	<3.0	<3.0
Chlorodibromomethane (µg/L)	<3.0	<3.0
Chloroform, total (µg/L)	<3.0	<3.0
Toluene, total (µg/L)	<3.0	<3.0
Benzene, total (µg/L)	<3.0	<3.0
Chlorobenzene (µg/L)	<3.0	<3.0
Chloroethane (µg/L)	<3.0	<3.0
Ethylbenzene, total (µg/L)	<3.0	<3.0
Trichlorofluoromethane (µg/L)	<3.0	<3.0
1,1-Dichloroethane, total (µg/L)	<3.0	<3.0
Dichloroethylene, total (µg/L)	<3.0	<3.0
Trichloroethane (µg/L)	<3.0	<3.0
Tetrachloroethane, total (µg/L)	<3.0	<3.0
Dichlorobenzene, total (µg/L)	<3.0	<3.0
Dichloropropane, total (µg/L)	<3.0	<3.0
Trans dichloroethene, total (µg/L)	<3.0	<3.0
Dichloropropene, total (µg/L)	<3.0	<3.0
1,3-Dichlorobenzene, total (µg/L)	<3.0	<3.0
1,4-Dichlorobenzene, total (µg/L)	<3.0	<3.0
Chloroethylvinylether, total (µg/L)	<3.0	<3.0
Dichlorodifluoromethane, total (µg/L)	<3.0	<3.0
Trans-1,3-Dichloropropene (µg/L)	<3.0	<3.0
Cis-1,3-Dichloropropene (µg/L)	<3.0	<3.0
Vinylchloride (µg/L)	<3.0	<3.0
Trichloroethylene (µg/L)	<3.0	<3.0
Styrene, total (µg/L)	<3.0	<3.0
1,2-Dibromoethane, total (µg/L)	<3.0	<3.0
Xylene, total (µg/L)	<3.0	<3.0
Tritium, total (pCi/L)	50	45

Refined Conceptual Hydrogeologic Model

Hydrogeologic testing at the well field provided information that helped refine the conceptual hydrogeologic model of ground-water flow to the supply well. The following are the major points of refinement.

1. The aquifer consists of as much as 70 ft of regolith and highly weathered bedrock overlying competent, sparsely fractured schist. On the basis of borehole-flow measurements, most water enters supply well SW6 from fractures between 40 and 60 ft below land surface. Because most water is encountered at a shallow depth, the area contributing recharge is likely to be situated immediately surrounding the supply well. However, water-producing fractures in the competent bedrock were identified as deep as 219 ft below land surface, and borehole geophysical logging conducted while pumping supply well SW6 showed two fractures, one as deep as 169 ft below land surface, were hydraulically connected to the fractures yielding water to SW6. This indicates some ground-water flow is at depths at least 169 ft below land surface and possibly as deep as 219 ft below land surface. The flow regime of the water-producing fracture network is complex and remains poorly understood.

2. As evidenced from the immediate response to pumping and large magnitude of drawdown in well D12 during the aquifer test at well SW6, water-producing fractures in well SW6 are known to be hydraulically connected to domestic-supply well D12. Good hydraulic connection is evident in that the drawdown in D12 is nearly equal to that in the pumped well, SW6. One possible explanation of this connection is by way of a nearly vertical north-south trending fracture or fractures. Drawdown caused by pumping SW6 is greatest along this trend. An examination of figure 9 indicates that a hydraulic connection through horizontal fractures, fractures parallel to the foliation, or the weathered bedrock would not explain why large drawdown is measured only at well D12. However, other fracture connections that do not trend north and south could be construed to produce a similar hydraulic response.

3. Rapid water-level fluctuations in response to natural recharge and to ground-water withdrawals indicate that the regolith and fractured crystalline-bedrock aquifer are well connected hydraulically. The 48-hour aquifer test showed water pumped from supply well SW6 during the test came from the release of water from storage within the regolith. The fractures in the schist providing the transmissive pathways for ground-water movement to supply well SW6 are hydraulically well connected to the shallow regolith and upper highly weathered part of the bedrock.

4. Slug-test results indicate that transmissivity of the schist in the well field ranges from 2.4 ft^2/d at OB4 to 2,850 ft^2/d at SW6; the average is about 60 ft^2/d. The nonuniform distribution of transmissivity throughout the well field indicates that the geometry and interconnection of water-producing fractures probably vary considerably, water-producing fractures are not evenly distributed, and ground-water velocities must vary greatly throughout the well field.

5. The magnitude of drawdown observed in supply well SW6 during the 48-hour constant-discharge aquifer test indicates that the well may not be able to sustain a long-term yield of 50 gal/min because the major water-yielding fractures between 40 and 60 ft below land surface will become dewatered.

6. Nitrate and tritium analyses of ground water from supply well SW6 supported the other evidence that the source of water contributed to the well was from near the wellhead.

Contributing-Area Delineations

This section describes results from various approaches to delineate the contributing area to supply well SW6. Preliminary delineations were made using simple water-budget and time-of-travel equations, then three approaches to refine the delineations were illustrated.

Preliminary Delineations

A water budget and time-of-travel equation were used to provide preliminary delineations of the contributing area and 90-day time-of-travel area to supply well SW6. These are simple delineations that require little data and are based on assumptions that do not incorporate the hydrogeologic complexities identified in the conceptual model. Nevertheless, the delineations provide initial estimates of the surface area of the aquifer that may be included in the WHP area.

Because supply well SW6 is located in an upland area near the divide between Muddy and Deer Creeks, streamflow is unlikely to be induced to the well from streams in the manner shown in figure 2. Thus, the contributing area for supply well SW6 is the same as its area of diversion (no additional adjacent areas contribute water).

Contributing Area Using Water Budget

A steady-state water budget provides the first approximation of the limits of aquifer surface area needed to provide recharge to supply well SW6. This can be computed as:

$$A = \frac{Q}{W}, \tag{1}$$

where A is the aquifer area needed to provide recharge, in square feet;

Q is pumping rate, in cubic feet per year; and

W is ground-water recharge rate, in feet per year.

According to equation 1, if ground-water recharge is about 9 in / yr (0.75 ft / yr), a surface area of about 0.17 mi^2 is needed to capture enough recharge to provide 50 gal / min (3.5 million ft^3 / yr) for supply well SW6. Recharge of 9 in / yr is a median within the range of recharge rates reported in the initial conceptual model. The shape of the recharge area cannot be determined from equation 1, but it is shown as a circle with radius of 1,220 ft surrounding well SW6 (fig. 17). The circle extends beyond the watershed boundaries of the small tributary to Ebaugh Creek, indicating that the contributing area might include some area in the Muddy Creek Basin. Although ground-water divides are usually assumed to coincide with watershed divides, ground-water divides are not fixed; they can move in response to ground-water withdrawals as discussed in Risser and Madden (1994, p. 24).

Note that the water-budget computation provides an estimate of the aquifer surface area providing recharge. For this preliminary estimate of contributing area, the area providing recharge and the contributing area are assumed to be coincident, although this is not necessarily the case as shown in figure 18. Because step-drawdown tests, geophysical logging, and ground-water sampling indicated that supply well SW6 produces from shallow water-producing zones, it is reasonable to assume that the area providing recharge is not far removed from the wellhead.

Time-of-Travel Area Using Fixed-Radius Method

An approximation of the radius of a 90-day time-of-travel area for a well with a pumping rate of 50 gal / min was delineated by use of the fixed-radius (volumetric-flow) method (Risser and Madden, 1994, p. 26; U.S. Environmental Protection Agency, 1987, p. 4-6). The approach gives the radius of an area that is assumed to be circular with its focus at the well and is defined as:

$$R = \left[\frac{Qt}{\pi b \theta}\right]^{\frac{1}{2}}, \tag{2}$$

where R is radius of time-of-travel area, in feet;

Q is pumping rate, in cubic feet per day;

t is traveltime of interest, in days;

b is aquifer thickness, in feet; and

θ is porosity of the aquifer.

Values of porosity (θ) and aquifer thickness (b) are not well known, but were estimated as 0.08 and about 70 ft, respectively, from the specific yield and other properties of the schist as described for the initial and refined conceptual models. The radius of the 90-day time-of-travel area computed with this approach is 222 ft, which defines a circle with an area of about 0.0055 mi^2 (fig. 17). The 90-day time-of-travel area is only a small part (about 3 percent) of the contributing-area size as estimated from the water budget.

Refinements to Preliminary Delineations

Three approaches were used to refine the delineation of contributing area: (1) uniform-flow equation, (2) superposition of drawdown, and (3) numerical modeling. Results from these approaches are discussed and compared in this section.

Because ground-water flow to SW6 appears to be at least in part transmitted by discrete fractures that are not evenly distributed, ground-water velocities are very difficult to estimate. Thus, the time-of-travel area was not refined. The time-of-travel area is best supported with data on flow velocity determined from the use of tracers. Tracers can provide an estimate of effective porosity of the

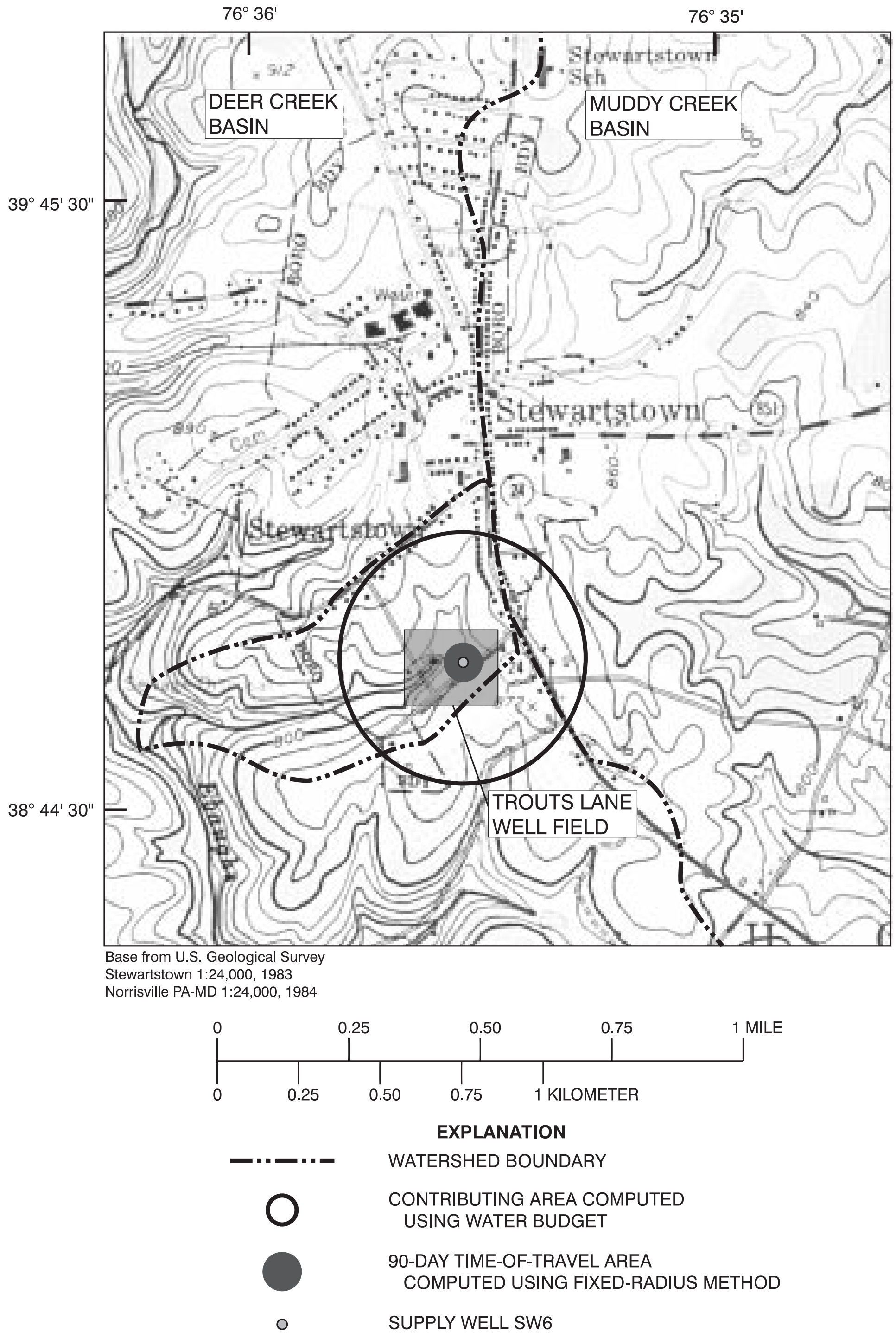


Figure 17. Preliminary delineation of contributing area and 90-day time-of-travel area for pumping 50 gallons per minute at Trouts Lane supply well SW6, Stewartstown, Pa.

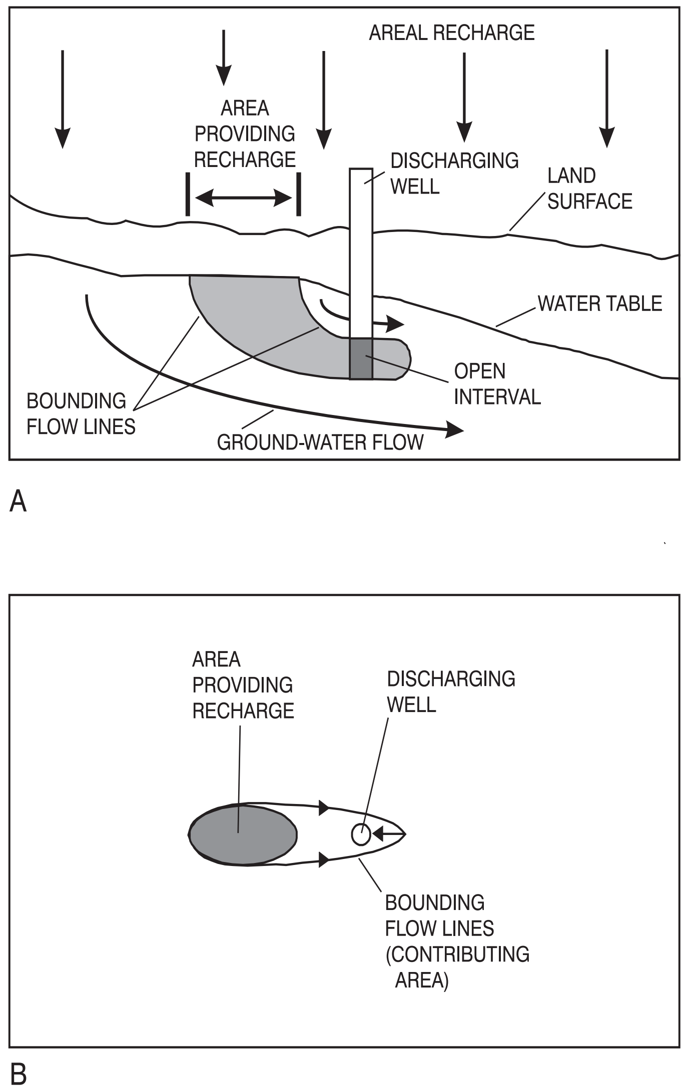


Figure 18. Aquifer surface area providing recharge to a single discharging well in a simplified hypothetical ground-water system. (A) cross-sectional view, (B) map view. (Modified slightly from Reilly and Pollick, 1993, fig. 1.)

aquifer and confirm some travel paths. For example, on the basis of tracer-test results, an effective porosity of 0.001 was used in a well field model of ground-water flow in a fractured crystalline-bedrock aquifer at Mirror Lake, N.H., (Lane and others, 1998) that is similar to the fractured schist at the Trouts Lane well field. This very small value of effective porosity is nearly two orders of magnitude less than the estimate of 0.08 used in this study to approximate the 90-day time-of-travel area shown in figure Figure. If an effective porosity of 0.001 was used in the time-of-travel equation, the radius of the circular time-of-travel area would increase by a factor of about 9. Tracer tests were not used at this well field because it was feared they would affect the nearby domestic-supply wells.

An approach for refining the 90-day time-of-travel area shown in figure 17 that is consistent with the refined conceptual model would be to extend the circle with a radius of 222 ft along the north-south trend of maximum drawdown shown in figure 15A, making the delineation long and narrow (elliptical) rather than circular. However, because the effective porosity is not well known, the size of the area could be greatly in error.

Uniform-Flow Equation

The uniform-flow equation (Todd, 1980, p. 121) was used to estimate the contributing area for supply well SW6. The contributing area was delineated by computing the stagnation point and position of the outer bounding flow path as described in Risser and Madden (1994, p. 32) according to the equations

$$P = \frac{-Q}{2\pi Kbi} \tag{3}$$

$$L = 2\pi P \tag{4}$$

$$x = \frac{-y}{\tan\left(\frac{-y}{P}\right)} \tag{5}$$

where P is distance from the well to the stagnation point, in feet;

L is the width between the asymptotic limits separating flow to the well from flow past the well, in feet;

Q is pumping rate, in cubic feet per day;

K is hydraulic conductivity, in feet per day;

b is aquifer thickness, in feet;

i is uniform slope of the prepumping potentiometric surface, in feet per foot;

x is coordinate distance of a point on the limiting flow line parallel to the uniform flow; and

y is coordinate distance of a point on the limiting flow line perpendicular to the uniform flow.

All angles are in radians.

The contributing area for a withdrawal rate of 50 gal / min, aquifer transmissivity (Kb) of 60 ft / day, and ground-water gradient of 0.04 is shown in figure 19. The transmissivity was estimated from slug tests, and the gradient was determined from mapping the water-table configuration (fig. 5). The upgradient boundary was terminated where its size was large enough (0.17 mi^2) to capture 50 gal / min of recharge if the average recharge rate is 9 in / yr. Results of some computations from the uniform-flow equation are shown below.

Distance upgradient (+) or downgradient (-) from supply well SW6, in feet (x coordinate in equation 5)	Width of contributing area, in feet (equals 2y in equation 5)
-638	0 (stagnation point)
-502	1,000
0	2,005
1,484	3,000
3,290	3,400

A uniformly sloping water table is assumed with the uniform-flow method, which was not observed at the site. Also, supply well SW6 is located near the divide between the Deer and Muddy Creek Basins. Note that to capture 50 gal / min, the contributing area must extend across the ground-water divide (fig. 19). Although the pumping could cause the ground-water divide to shift, this shift is not accounted for in the uniform-flow method.

Water-Table Mapping

The contributing area to supply well SW6 also was delineated from a map representing the water table during pumping as discussed in Risser and Madden (1994, fig. 25). A water-table map was made to represent conditions during pumping by superimposing the drawdown measured at the end of 48 hours of pumping (fig. 15A) during the aquifer test conducted April 17-19, 1991, from the estimated pre-pumping water-table surface (fig. 10). From the resultant water-table map, the contributing area was delineated by sketching the bounding flow lines captured by supply well SW6 as shown in figure 20. When sketching the flow lines, the aquifer was assumed to be homogeneous and isotropic.

Sketching the flow lines captured by supply well SW6 delineates a contributing area much too small for withdrawals of 50 gal / min. If the ground-water recharge rate is 9 in / yr, the well needs to capture recharge from 0.17 mi^2 of aquifer surface to produce 50 gal / min. However, the contributing area computed with the superposition

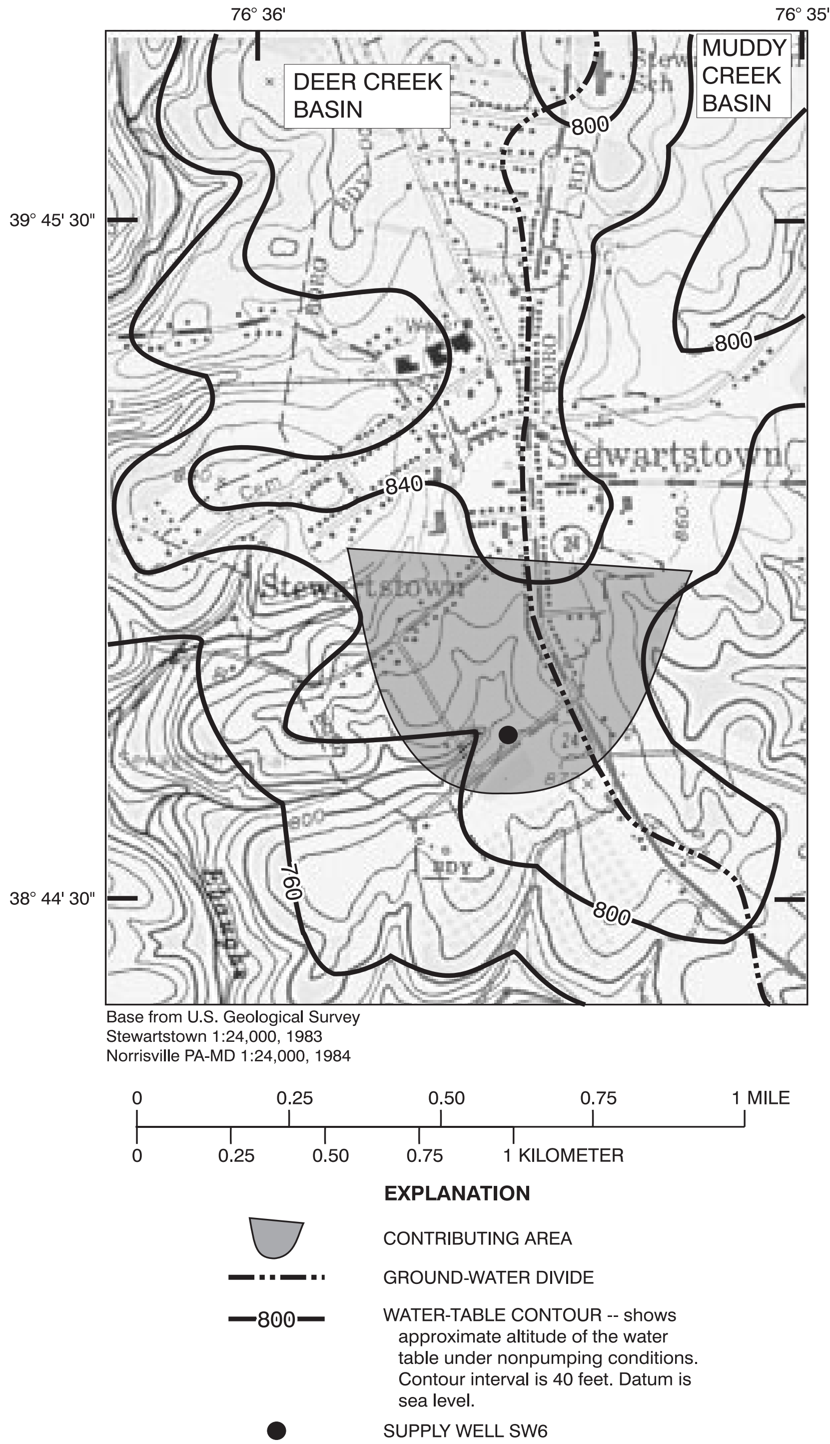


Figure 19. Contributing area for pumping 50 gallons per minute from Trouts Lane supply well SW6, Stewartstown, Pa., estimated using the uniform-flow equation.

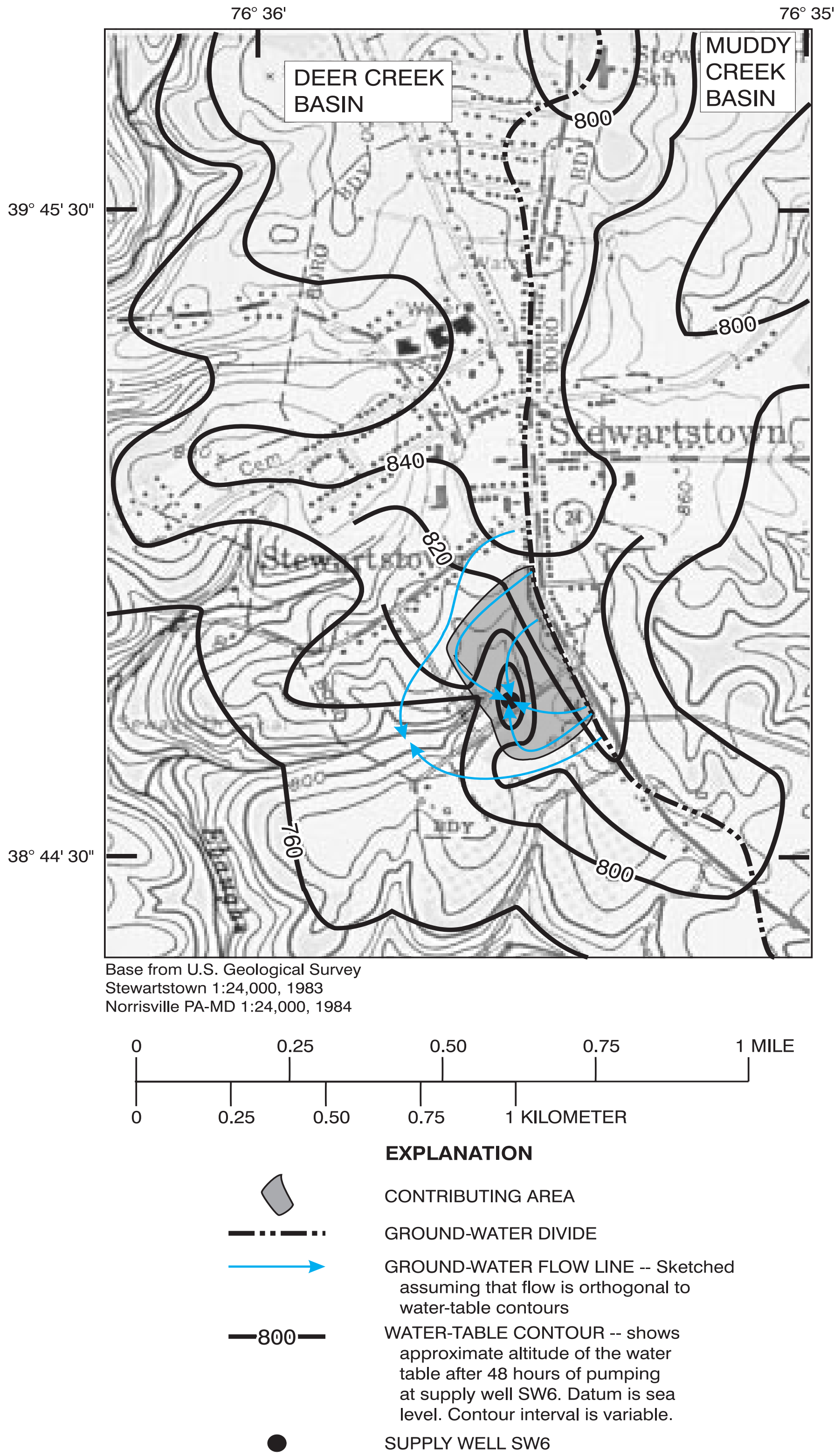


Figure 20. Contributing area for pumping 50 gallons per minute from Trouts Lane supply well SW6, Stewartstown, Pa., estimated by superposition of drawdown.

method is only about 0.045 mi^2 (about one-fourth the necessary area). This difference is probably because not enough observation wells were available to map the water table with sufficient detail to accurately delineate ground-water-flow paths in the vicinity of supply well SW6.

An advantage of the water-table mapping approach over other approaches is that actual water levels measured at the well field are used to prepare a water-table map. Thus, some anisotropy and heterogeneities reflected in the drawdown are directly incorporated into the contributing area. One problem with the use of the method at this site is that the pumping from the 48-hour aquifer test at well SW6 was not of sufficient duration to establish a steady-state zone of influence. This shortcoming could be partly improved by use of drawdown extrapolated for a longer duration. Other problems are that the water-table map at the regional scale is approximate, and drawdown was only measured locally at the well field at a few locations; thus, the drawdown extent beyond the well field is unknown. A test of longer duration and additional monitoring wells beyond the extent of the well-field area would allow more successful application of this method. In practice, however, it is rare to be able to map the water table accurately enough to define the position of the bounding flow lines that are captured by the well.

Refining the contributing area by use of a water-table map illustrates the important effect of the nonuniform water-table slope and anisotropy on the shape of the contributing area. Although the extent of this area is too small, its elongate shape differs greatly from and is more realistic than the preliminary circular contributing-area delineation (fig. 17).

Numerical Modeling

A 3-dimensional numerical ground-water-flow model including the Trouts Lane well field and surrounding area was prepared to delineate a contributing area for supply well SW6. A finite-difference computer code (McDonald and Harbaugh, 1988) was used with a particle-tracking program (Pollock, 1994) for model simulations. The area was divided into a finite-difference grid with 45 rows and 41 columns (fig. 21). The horizontal dimensions of the cells were varied so that the smallest cells, 100 ft by 100 ft, surrounded supply well SW6. The area was divided vertically into 2 layers (fig. 22). The geometry, boundary conditions, and hydraulic properties used in the model are summarized in table 4.

The model was prepared with information on the hydrogeologic framework and aquifer properties derived from hydrologic testing at the field site. The Wissahickon Formation was simulated with two model layers as shown in figure 22. Layer 1, which extends from land surface to a depth of 70 ft below land surface, simulates the regolith and upper highly weathered part of the Wissahickon Formation. Layer 2 represents the sparsely fractured schist from 70 to 220 ft below land surface. The base of layer 2 at 220 ft below land surface is the depth of the deepest water-yielding fracture indicated from geophysical logging. Note from the cross section along row 26 of the model (fig. 22) that the water table is below the bottom of layer 1 in some places. The transmissivity of the aquifer was estimated to be about 60 ft^2/d, which is the geometric mean determined from slug-test results. Because most water to supply well SW6 is contributed from fractures at depths less than 70 ft below land surface, most transmissivity of the simulated aquifer is assigned to layer 1. Thus, the horizontal hydraulic conductivity of layer 1 was assigned a value of 1 ft/d. The transmissivity of the layer would depend on its saturated thickness; for example, if 60 ft of layer 1 is saturated, the transmissivity would be 60 ft/d. The horizontal hydraulic conductivity of layer 2 in the Trouts Lane well field is probably much smaller than for layer 1; thus, it was assigned a value of 0.1 ft/d (10 percent of layer 1) to represent the less transmissive fractures at depths greater than 70 ft below land surface. The apparent good hydraulic connection along a north-south trend, shown by the large drawdown measured during the aquifer test (fig. 15), was simulated with a hydraulic conductivity of 8 ft/d (determined from the slug-test results of supply well SW6) in cells of both layers in column 16, rows 23-29. This created a 700-ft long zone of high hydraulic conductivity in the Trouts Lane well field that was meant to approximate the good hydraulic connection between supply well SW6 and observation wells D12 and OB4. Because the aquifer-test results could not be fit to an analytical solution for an anisotropic aquifer, anisotropy was not assigned in the ground-water-flow model.

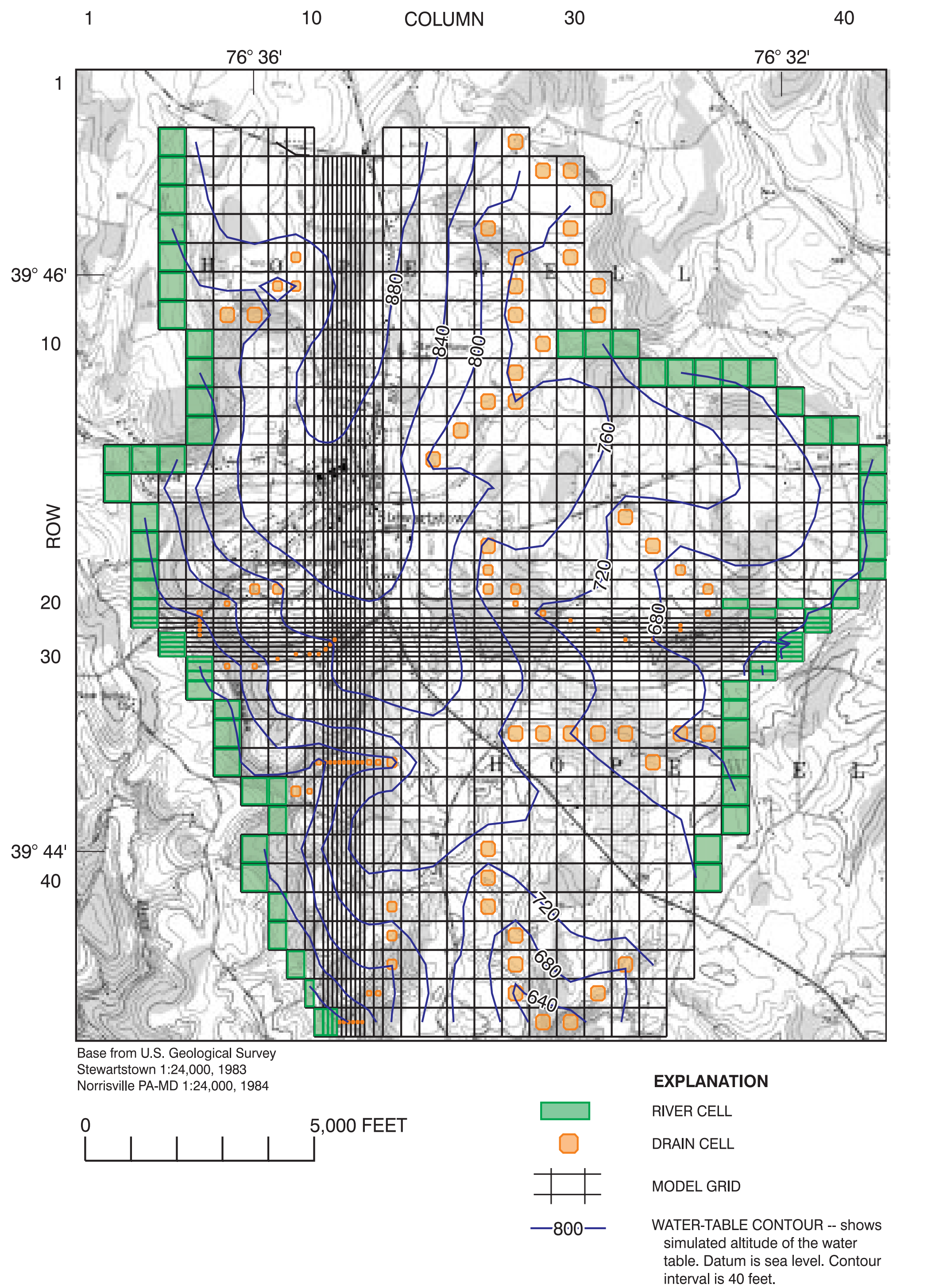


Figure 21. Finite-difference grid, boundaries, and simulated water-table altitude for ground-water flow model of the Trouts Lane well field and surrounding area, Stewartstown, Pa.

***Table 4.** Summary of parameters in the ground-water model of the Trouts Lane well field and vicinity, Stewartstown, Pa.*

[ft, feet; in/yr, inches per year; ft/d, feet per day]

MODEL GEOMETRY	
Grid	Variable-spaced, finite-difference grid contains 45 rows and 41 columns. Horizontal cell-face dimensions range from 100 × 100 ft to 600 × 600 ft.
Layers	Two layers—Layer 1 represents the aquifer under unconfined conditions. Bottom is everywhere 70 ft below land surface. Layer 2 represents the aquifer primarily under confined conditions, but can simulate unconfined conditions if needed. The base of layer 2 is 220 ft below land surface everywhere.
BOUNDARY CONDITIONS	
Base and lateral boundaries of model	The base of the model is simulated by no-flow cells located 220 ft below land surface. No-flow cells also surround the active model cells laterally.
Streams	First-order streams are simulated using head-dependent flux drain cells. Drain altitude was set at the stream stage. Other streams are simulated using head-dependent flux river cells. Bottom of stream was set 2 ft below river stage. Conductance of river and drain cells was set to 2 ft^{-1}.
Recharge	Recharge is simulated as a constant flux of 9 in / yr to the water table throughout the modeled area.
Well	Supply well SW6 is simulated by withdrawing a constant flux of 40 gal / min from the cell at layer 1, row 26, column 16.
HYDRAULIC PROPERTIES	
Horizontal hydraulic conductivity	The horizontal hydraulic conductivity is 1.0 ft / d in layer 1 and 0.1 ft / d in layer 2 except in cells in layers 1 and 2 in column 16, rows 23-29 where hydraulic conductivity is 8 ft / day.
Vertical hydraulic conductivity	Assumed to be equal to the horizontal hydraulic conductivity.

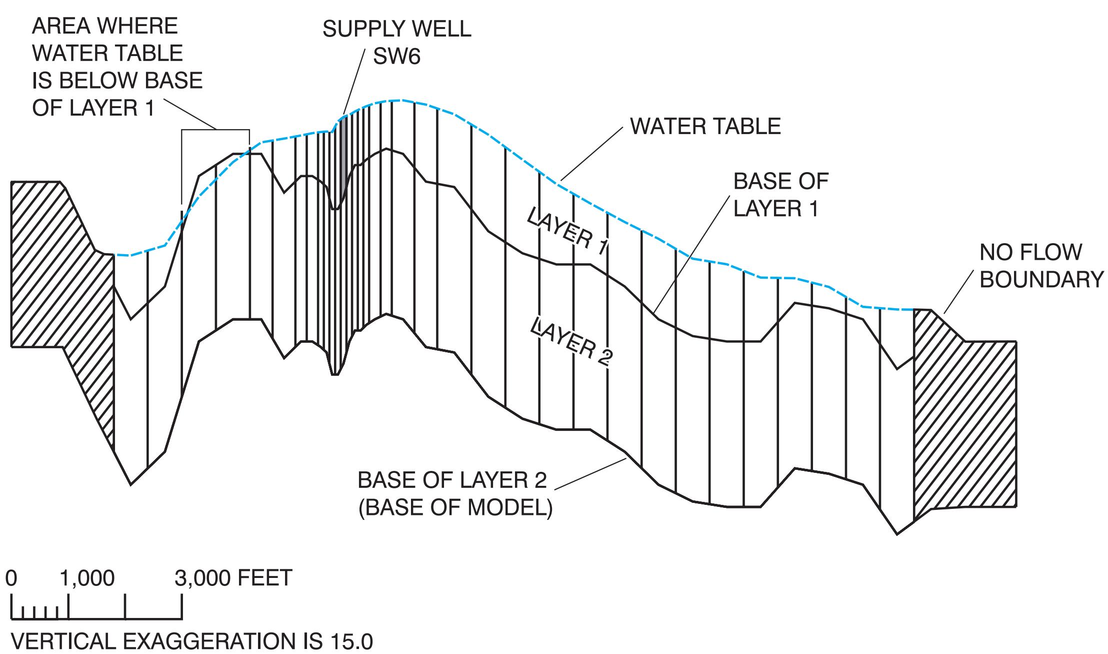


Figure 22. Section along row 26 of the ground-water-flow model of the Trouts Lane well field and surrounding area, Stewartstown, Pa.

The model was used to simulate the contributing area for supply well SW6 with few adjustments. The simulated steady-state water table was compared to the estimated water-table altitudes shown in figure 10. By use of a recharge of 9 in / yr, the hydraulic conductivities of 1.0 and 0.1 ft / d for layers 1 and 2, respectively, provided a reasonable simulated water-table configuration that was below the land-surface altitude. Calibration of the model could be improved by comparing the simulated water table to a water-table map prepared from water levels measured in wells and by comparing simulated and measured streamflow. Therefore, results from these simulations should be viewed as uncalibrated estimates.

Pumping of 40 gal / min from supply well SW6 was simulated as a withdrawal entirely from fractures at depths of less than 70 ft below land surface (layer 1). The contributing area delineated with the ground-water-flow model for withdrawals of 40 gal / min is shown in figure 23. Simulations indicated that withdrawals of 50 gal / min (the rate that has been used throughout this report for delineating the contributing area at supply well SW6) probably could not be sustained because the major water-yielding fractures would be dewatered. The contributing area shown in figure 23 is 0.135 mi^2. Recharge of 9 in / yr on this area provides the 40 gal / min that is captured by supply well SW6.

The advantages of model simulation over the other approaches described previously are that a steady-state pumping condition can be simulated and boundary conditions and major heterogeneities can be more easily simulated. The disadvantages of model simulation are that (1) laminar flow is assumed in the model through a granular-porous aquifer and not turbulent flow through a fractured crystalline-bedrock aquifer; and (2) model preparation and calibration are time consuming. Although very simple conditions of a 2-layer aquifer are assumed in this model, the boundary conditions and major heterogeneities (one linear fracture zone) are incorporated that are described in the refined conceptual hydrogeologic model.

COMPARISON OF DELINEATION METHODS

A water-budget equation was used to make a preliminary delineation of the contributing area for supply well SW6. Three other methods (uniform-flow equation, water-table mapping, and numerical modeling) were used to refine the contributing-area determined from the water budget. The fixed-radius method, based on a volumetric-flow computation, was used to estimate a 90-day time-of-travel area that was not refined further. These methods have differing data requirements that are summarized in table 5.

In general, methods that allow the most complete representation of the hydrogeologic framework and boundary conditions will provide the most accurate delineations of contributing area. For wells that obtain water from shallow fractures and do not induce substantial flow from a stream (such as supply well SW6), determining the water budget is a good method to estimate the size but not the shape of the area contributing recharge to the well. The uniform-flow method improves the shape of the contributing area delineated for supply well SW6 by allowing the incorporation of a sloping water-table surface. However, because the water table is assumed to be a uniformly sloping plane, the contributing area shape is simple and the upgradient limit of the area is not specified. Sketching the limiting flow lines to supply well SW6 from a water-table map incorporates the irregularities of the water-table surface and some of the aquifer heterogeneities. Unfortunately, the water-table map of the area could not be prepared with enough detail to provide an accurate delineation of the contributing area for supply well SW6. This will probably be the case in most field settings, but if a detailed map can be prepared, sketching ground-water flow paths to shallow wells could allow the contributing area to be reasonably delineated. Numerical modeling allowed the incorporation of a complex hydrogeologic framework and boundary conditions in the vicinity of supply well SW6. In this study, the highly transmissive fractures connecting supply well SW6 and domestic-supply well D12 were simulated as a line of cells with a hydraulic conductivity eight times greater than the surrounding cells.

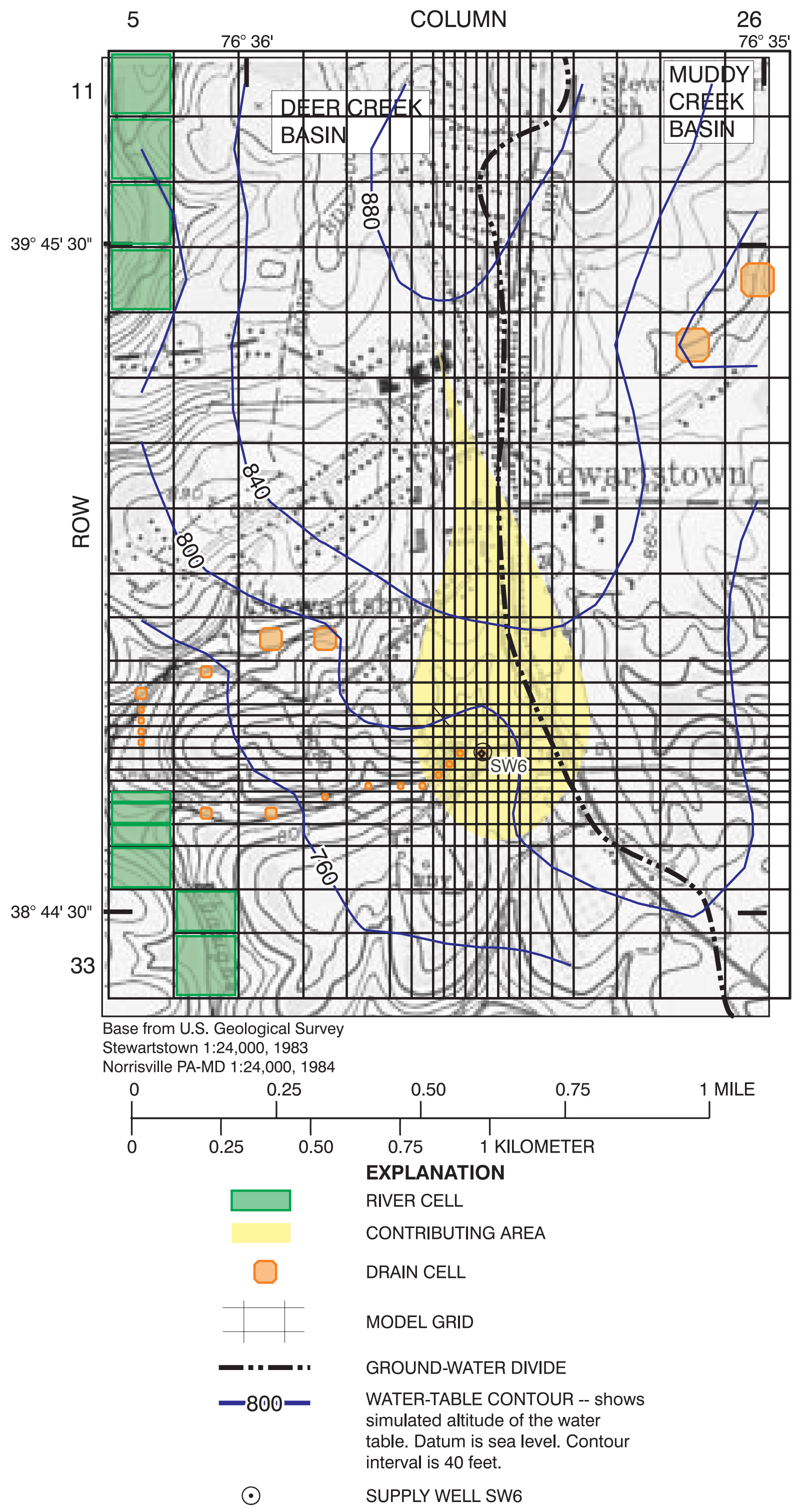


Figure 23. Contributing area for pumping 40 gallons per minute from Trouts Lane supply well SW6, Stewartstown, Pa., estimated using a ground-water-flow model.

***Table 5.** Comparison of minimum data requirements for each delineation method considered in this study*

[N/A, not applicable]

Data	Delineation Method				
	Water budget	Fixed radius (volumetric flow equation)	Uniform-flow equation	Water-table mapping	Numerical modeling
Pumping rate	Required	Required	Required	Suggested	Required
Estimate of recharge rate	Required	N/A	Suggested	Suggested	Required
Aquifer thickness	N/A	Required	Required	N/A	Required
Effective porosity	N/A	Required	N/A	N/A	Required for time-of-travel delineations
Hydraulic conductivity	N/A	N/A	Required	N/A	Required
Water-table map	N/A	N/A	Slope of prepumping water table is required.	Required	Suggested for calibration

SUMMARY AND CONCLUSIONS

Delineating a contributing area to a supply well completed in a fractured crystalline-bedrock aquifer at the Trouts Lane well field, Stewartstown, Pa., was completed based on a strategy for delineating the contributing area to a public-supply well. The strategy consists of (1) developing an initial conceptual hydrogeologic model, (2) developing a preliminary contributing-area delineation, (3) refining the initial conceptual hydrogeologic model by conducting field studies, and (4) revising the contributing-area delineation so it reflects the refined conceptual hydrogeologic model. The improved understanding of the ground-water-flow system led to a more defensible delineation of the contributing area.

An initial conceptual hydrogeologic model was developed from a review of literature pertaining to crystalline-rock terranes in the Piedmont Physiographic Province. Ground water in such terranes is present at shallow depths in the pore spaces of the regolith and in fractures in the bedrock. Usually, water for public supply is encountered in fractures within the competent bedrock, which are hydraulically connected to water stored in the overlying regolith.

Of primary importance for refining the initial conceptual hydrogeologic model was the constant-discharge aquifer test, water-level measurements in wells, and geophysical logging. Analysis of the aquifer tests and water-level fluctuations helped identify a north-south trending hydraulic connection that probably intersects supply well SW6 and a domestic well located about 200 ft south of the supply well. This possible hydraulic connection is not aligned with foliation of bedrock. The aquifer-test results showed that pumping supply well SW6 caused a north-south trending, elliptical cone-of-depression. The test also indicated fractures providing water to the supply well are hydraulically well-connected to water in the regolith. Slug-test results showed a nonuniform distribution of transmissivity throughout the well field, indicating that the water-producing fractures are not evenly distributed and ground-water velocities must vary considerably throughout the well field. Borehole geophysics and borehole-flow measurements indicated that most water entered the supply well through bedrock fractures at very shallow depths —less than 60 ft below land surface; therefore, the source of recharge contributed to the well is probably from the immediate vicinity of the well. Chemical analysis of ground water also provided some supporting evidence that pointed to a local source of ground water for the supply well.

Fracture-trace mapping was inconclusive, and thus, did not help refine the conceptual hydrogeologic model. Although a prolific water-producing fracture zone extends through supply well SW6 and across the well field, fracture-trace mapping did not identify any linear traces on aerial photos around the well field. Fracture-trace mapping of 120 straight-line stream segments identified two preferential bearings at N. 30° E. and N. 50° W.; however, these bearings are not aligned with the direction of preferential drawdown measured during the aquifer test at supply well SW6.

Additional investigations would help further refine the conceptual hydrogeologic model for the well field and vicinity. The importance of an accurate water-table map for the region surrounding the well field cannot be overemphasized. Nearly every method to delineate a contributing area requires an estimate of the regional water-table configuration. For this study, the water-table map was approximated on the basis of a few water-level measurements and topography. Also, an aquifer test designed to monitor the zone of influence of the supply well throughout a larger extent of the regolith and bedrock can better define the location and extent of the major water-producing fracture in the bedrock. The test would require the installation of additional piezometers and bedrock wells.

A steady-state water budget and a time-of-travel equation were used to provide preliminary delineations of the contributing area and 90-day time-of-travel area. Assumptions inherent in the method were not consistent with the conceptual hydrogeologic model; however, the steady-state water budget provided a preliminary indication of the maximum size of the contributing area. Three approaches were used to refine the contributing-area delineation: (1) uniform-flow equation, (2) water-table mapping, and (3) numerical modeling. Contributing-area shapes differed for the three methods because each method allowed only certain complexities of the hydrogeologic system to be included. The ground-water-flow model was a very simplified approximation of this fractured crystalline-bedrock aquifer.

A major limitation of this investigation was the inability to refine the delineation of the time-of-travel area. Because a few discrete fractures probably supply a substantial amount of water to SW6, the effective porosity (and hence traveltime) of ground water is probably best estimated by use of tracers.

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